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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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Design to Cost and Life Cycle Cost

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Conference Proceedings No.289

DESIGN TO COST AND LIFE CYCLE COST

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Papers presented at the Flight Mechanics Panel Symposium on Design to Cost and Life Cycle Cost
held in Amsterdam, Netherlands, 19–22 May 1980.

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PREFACE

The increased complexity of aircraft, growing social requirements for government funds and high rates of inflation have strongly focussed attention on aircraft systems costs. Any well-engineered system includes minimum cost as a criterion to be considered along with performance requirements. It has always been recognized that this cost means overall cost to the user including fuel and maintenance as well as initial cost. Some products may be built to a minimum first cost without regard to later costs incurred as a result of initial cost savings. Presumably if this is overdone, the marketplace will shun the product and a more rational balanced design will win out. In the very special marketplace for commercial and military aircraft, however, long product life and the small number of actual builders, usually one for the military case, leaves the user of a poor design severely penalized for a long period of time. To help avoid major errors of this sort attempts have been made to formalize logical processes for optimizing costs, both initially and over the life of the product. The former has been called Design to Cost (DTC) and the overall cost analysis has been defined as Life Cycle Cost (LCC).

A symposium to explore the state of the technology of DTC and LCC was held by the AGARD Flight Mechanics Panel in Amsterdam, The Netherlands, from May 19 to May 22, 1980. Twenty-six papers were presented in four sessions:

I. LCC Methodology and Its Relation to Specifications and Requirements.

II. Impact of LCC Analysis on Total System Design.

III. Cost Control of Operations and Support

IV. LCC of Subsystems and Components.

The papers included in these proceedings give a good overview of the approaches used in both industry and government to control costs and to optimize the engineering design to produce the most efficient aircraft possible. It seems clear that DTC is an incorrect expression since having set down specified requirements, it may be impossible to meet some equally tightly specified cost. The best one can hope for is the lowest cost to do the specified job. The question of the usefulness or the correctness of the specified requirements is often not attacked but it may be more important than all the DTC and LCC efforts to reduce life cycle costs. Once the requirements are laid down, the controllability of life cycle costs is greatest in the early conceptual phase, when uncertainty in cost estimation is largest. Hence, creative advanced design is a key for cost control.

Evaluating the relative importance of minimum initial acquisition costs and minimum life cycle costs is extremely difficult due to the reduced present value of future savings, e.g. savings in fuel or future maintenance, combined with the uncertainty of future interest rates and inflation. In addition, limited military budgets and a lack of multiyear funding tend to greatly increase the emphasis on initial costs, leaving the future operating and maintenance costs as problems for whomever is responsible at some future time.

The various papers in these proceedings deal in varying degrees with these problems but the overall theme is determining and minimizing costs. Good engineering is the primary key. Engineering for reliability, maintainability, low fuel consumption and good performance does not necessarily increase initial costs but in many cases trade-off studies are required to ascertain the cost/benefit ratio of a design feature. Many of the methods used will be found in these proceedings.

The meeting was well attended and the active discussion throughout the meeting showed the high degree of interest in the papers. The main themes of the discussions after each paper and during the round table will be included in the forthcoming Technical Evaluation Report (AGARD Advisory Report AR-165).

P.HAMEL
R.S.SHEVELL
Members,
Flight Mechanics Panel

CONTENTS

LIFE CYCLE COST ANALYSIS (LCCA) IN MILITARY AIRCRAFT PROCUREMENT

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The paper discusses changing economic environment, and the developing requirement to put increased emphasis on downstream activities in the early phases of a weapon system programme. A possible approach to calculating the magnitude and spread of cost reducing investments is considered, and applications of Life Cycle Cost Analysis in Strategic Decision Making, the Design Process, and as a sales aid are mentioned.

1. CHANGE IN ECONOMIC CLIMATE

The LCCA approach to decision making is developing into an increasingly important tool for policy making and procurement decisions at high management levels as well as for detailed trade-off studies and design optimisation. It seems the inevitable product of a most dramatic change in the rate of industrial and economic growth within the industrialised western world.

The Second World War focused the attention of many great nations on engineering expansion which provided levels of skills and employment that had not been required previously. The uneasy peace that followed included a decade of re-construction, re-organisation and political re-alignment, where those who had suffered most seemed to exhibit the greatest determination in eschewing war and developing international trade.

Towards the end of the 40s and during the early 50s, the rationing and deprivation of the past were quickly fading memories, near-full employment, economic stability, apparently limitless opportunities heralded the euphoric expansion of the late 50s. During these boom years of economic growth and relative stability of the currency, capital goods were ordered, consumer goods purchased in ever increasing volumes and a period of unparalleled growth followed. Relatively little heed seems to have been taken of the downstream costs of procurement decision, and the fact that this industrial and economic growth could not be sustained was understood only by a few academics, philosophers and researchers into the subject. (ref 1 - 'The Limits to Growth'). The subject as a whole, completely failed to catch the public imagination.

In the early 70s there certainly was a realisation that expansion could not continue indefinitely. However, in the UK, at least there was a firm underlying belief in the principles of free trade, the undesirability of excessively oppressive import restrictions or the maintenance of trade monopolies. There was, therefore, a tacit assumption that market forces would make the necessary adjustments to demand for scarce resources when it became necessary, and that technology would provide alternatives when the price was right.

In 1973/4, when the newly organised OPEC Cartel unexpectedly decided to implement tactical and strategic marketing policies and exert positive control over their nations principle assets, the consumers were caught completely by surprise. The fact that a three fold price increase for petroleum products did little to stem demand although affecting a significant decline in the rate of economic growth, seems to sustain the theory that economic growth had been maintained largely by the availability of cheap energy. Whether or not energy is cheap at present is a matter for debate, however, it is clear that at present price levels, there are few developed nations that are not subject to severe economic constraints due to the slackening of growth. These constraints are currently focusing attention on the downstream costs of past procurement decisions, and we are forced to the conclusion that had we known what we now know, design and procurement philosophies in the 60s and early 70s would have emphasised noticeably different criteria.

In considering our current situation, we must critically review our objectives in the military aircraft procurement field. Clearly, our individual approach to this question will be unique to the nature and function of our particular product. It is evident that most procurement decisions for capital equipment can be made purely on a cost effectiveness basis, laying out predicted cash flows on the projected time scale possibly making subjective adjustments for criteria such as the user appeal etc., and then normalising the cash flows according to agreed conventions. With military equipment procurement, this process is made far more complex by the addition of a further dimension, namely, mission effectiveness. In order to simplify the position, one can ignore the situation that requires a limited defensive operation, and confine the analysis of military aircraft to peacetime and wartime.

1) Peacetime - cost effective requirement:

The objective is to maintain the best defensive capability and readiness possible with the available financial allocations

2) Wartime - mission effective requirement:

The objective is to be able to maintain the best sortie/kill rate possible with the available equipment/personnel.

It is immediately apparent that unless the potential customers' requirements are wholly offensive (when the mission effectiveness requirements would tend to predominate) a balance has to be achieved between the peacetime operation and wartime requirement.

For example, the aircraft with marginal fatigue life for peacetime operations (where average training sorties tend to be more arduous than predicted wartime sortie patterns), is well overweight and over engineered in respect of the mission effectiveness requirements (certainly if one takes account of likely attrition rates in defensive operation). Clearly, the optimisation of peacetime and wartime requirements needs a delicacy of judgement that is subject to a wide variation in policies and individual view points. It is apparent that a soundly based LCCA produce a peacetime solution only; however, it also presents a basic platform for making the cost/mission effective trade-offs using the sortie rate/pay load/range/kill rate analysis.

2. INVESTMENT IN DESIGN TO COST/LIFE CYCLE COST TECHNIQUES AND POSSIBLE RETURNS

In considering the investment required and possible returns, it is appropriate to look at a particular example; the one described is broadly typical of the cash flow programme that might be expected of the next generation of Combat Aircraft. The cash flows indicated in Fig. 1 are representative of the costs of 260 Medium Weight Combat Aircraft when broadly following UK cost allocations and accounting conventions. It is of course assumed that in organisations where there are no formal DTC/LCC functions, the requirements for maintaining a competitive position in the market place are being met even if the full benefits of a rigorously applied cost reduction discipline is not available. Certainly, Value Engineering Departments, Production Liaison Groups, Planning Engineers etc. have a vital role in keeping down unit costs, and these functions are an important ingredient in the overall requirement to reduce LCC. However, it is common experience of practitioners in these disciplines that their efforts are frequently devoted to cost reduction exercises that would have been much more economically undertaken at an earlier stage in the programme. In fact, one sometimes sees the situation where high cost designs, materials and processes are initiated in the feasibility phase without adequate consideration of the cost implication, and decisions are made and implemented which subsequently have to be followed up by expensive cost reduction exercises in attempting to recover the situation.

The matter of when to invest in cost reduction techniques is the key to the overall solution of problems by life cycle cost analysis techniques. If one considers the overall military aircraft programme previously described, the framework for calculating the investment requirements must include certain specific assumptions.

2.1 The relationship between LCC already determined and time into the project

It seems sensible to assume that as a project proceeds, the configuration is fixed, materials and production processes are defined, servicing procedures are established etc. One becomes committed to an increasing percentage of the outstanding LCC and the remainder that is still subject to possible reduction becomes progressively smaller. It would be extremely useful if some form of agreed model could be developed in order to establish a consistent baseline for decision making purposes. To indicate what is required, we need to look for a very simple relationship analogous to the negative exponential used that is now well understood and a useful (if over simplified) predictor of likely cost reduction with quantity produced.

Unfortunately, we have yet to find anything as simple for our purpose; nevertheless, that has not prevented us from experimenting with some slightly more complex relationships to ascertain whether they make any sort of sense. If one takes the starting point as being a basically Pareto type of relationship where 80% of the LCC is committed when 20% of the project life cycle has elapsed and then develop from this a family of alternatives (ie 70/30, 90/10 etc.) it should be possible to pick one of them and postulate that it will adequately represent the relationship between LCC committed and yet to be committed.

Relationships of the form: $$y = 100\left[1-e^{-\left(\frac{1+23t}{100}\right)}\right] \quad 90/10$$

$$y = 100\left[1-e^{-\left(\frac{1+8t}{100}\right)}\right] \quad 80/20$$

$$y = 100\left[1-e^{-\left(\frac{1+4t}{100}\right)}\right] \quad 70/30$$

give reasonable looking relationships, which are tabulated against the cumulative programme costs (Fig. 2).

Time into Project %	90/10	80/20	70/30
0	1	1	1
10	90.07	55.51	33.63
20	99.90	80.01	55.51
30	99.98	91.02	70.18
40	99.99	95.96	80.01
50	100	98.19	86.60
60	100	99.19	91.02
70	100	99.63	93.98
80	100	99.84	95.96
90	100	99.93	97.29
100	100	100	100

2.2 Assumptions on expected benefits

If one had the resources available to investigate a completed representative project, and analyse the cost savings that would have been available, had logical and timely decisions been made at every point in the programme, it would be possible to make an assessment of the potential for cost reduction available in a future project. One could then make an assessment of the benefits that might be achievable by adjustments to the spend pattern on some future project. I trust someone will be able to do this sometime in the future.

However, in the absence of any firm information on the matter, I will make the assumption that additional investment in the following phases, definition, development, production investment and initial support is capable of effecting a 2% reduction in the outstanding undetermined life cycle cost. Please do not ask for this figure to be substantiated, it is merely an assumption; however, I believe it may be a very conservative assessment of the achievable savings, and therefore adequately takes into account the levels of uncertainty inherent in life cycle cost investigations.

Clearly, this is a rather broad assumption as the benefits that would accrue by investment in a particular phase could not be expected to occur proportionally within subsequent phases.

For instance, increased spend in the production investment phase aimed at reducing total life cycle cost is likely to have a greater effect on production than later phases.

2.3 Required real rate of return

A suitable rate of return must be chosen that adequately reflects the cost of capital and the opportunity costs of alternative investments, and for the purpose of this illustration 10% will be used. It should be noted that where constant economic conditions are assumed, the effects of inflation can be ignored.

Having made these assumptions, the amount that should be invested in LCC reduction and the timing of those investments can be calculated. The annual investment that will give a required real rate of return if the projected LCC reductions are achieved would be evaluated most accurately using a suitable computer programme to calculate the cash flows on an annual or possibly monthly basis, and in this respect would be even more useful if it included facilities to model the commitment curve, the benefits hoped for and the required rate of return. If this exercise is extended to comparing the effects of investment in projects that occupy differing time frames, then it will be necessary to reduce the cash flows to their net present values using the real rate of returns required (exclusive of an inflation allowance if constant economic conditions are used) as a discounting factor.

3. ASSESSMENT OF REQUIRED SPREAD OF INVESTMENT BY PHASE

Let us now summarise the assumptions made so far:

1) The time commitment curve follows the relationship previously described and for the purpose of the example that follows, the 80/20 assumption will be used.

2) Additional expenditure in each phase is capable of reducing the un-committed LCC by 2%.

3) A real rate of return of 10% is required.

In order to simplify the example for the purpose of illustrating the point, these further assumptions are also made.

4) Outstanding cash flows are treated as if they occur in the year in which they achieve 50% of their total. This allows a simple calculation of investment required to achieve the targeted rate of return.

5) The additional expenditure in each phase is assumed to be effective in the year in which the phase expenditure reaches 50%.

By using these assumptions the investment required can be calculated. See Fig 3. The table indicates that on the basis of the assumptions made, it is worth investing an additional £20M in a project definition phase, £9.9M in development and £4.1M in production investment.

These figures are really quite startling even bearing in mind the broad assumptions made and relative crudity of the calculations. The conclusion that one is led to is that if LCC analysis is to be of any real use in terms of making a significant improvement in the product and hence profitability for the manufacturers, the main incremental investments must be made early in the life cycle.

3.1 Effect of LCC Analysis on Acquisition Cost

It would be possible to use the assumptions stated previously, and calculate the effect of incremental investment in LCC on the acquisition cost alone by certain levels of investment, in particular phases. In theory it seems reasonable to assume that while there would be a considerable penalty in the acquisition phases of a programme that took no account whatsoever of downstream costs, it is self evident that this is a totally unrealistic situation in that even in the heyday of design to acquisition costs, downstream costs were never totally ignored. It was simply that they received much less emphasis than is current practice.

The conclusion that one comes to is that if there is a penalty (and this depends on whether the value of real rate of return required favours acquisition or operating phases) it will be an insignificant increment on the total acquisition costs.

4. SIGNIFICANT APPLICATIONS OF LCC ANALYSIS IN PERSPECTIVE

Before describing some of the main applications of LCC analysis it is worthwhile commenting that the current interest in LCCA donates a basic change in emphasis rather than a fundamental change in direction in the field of weapon system, design, manufacture and procurement. The key to the application of LCCA techniques is in the ability to produce timely and soundly based analysis. It goes without saying that the level of expertise and professionalism required from the analysts is of a very high order. The subsequent paper (ref 2) covers the subject of analysis and application in some detail and indicates the depths to which analysts must delve into past data, and the sophistication of modelling tools required to enable the techniques to be affectively applied.

4.1 Strategic Decision Making

In order that a Government or a Contractor can make an appropriate series of decisions leading to the requirement for a weapon system programme to meet a definite threat, an analysis of the total LCC of competing systems is an essential part of the process that leads to the optimised decision. This blunt statement now needs to be qualified in terms of how rigorously it can be followed in a real life decision making situation. If one used the UK procurement machinery as an example it would probably be fair to say that total LCC has always been used as a decision making criterion, however, with a degree of informality that would no longer be appropriate in the changing economic circumstances we find ourselves in. The use of LCC analysis in strategic decision making should be seen as a developing art with considerable scientific backing rather than rigorously applied numeric procedure. In practice a decision maker must be supplied with a framework of cost and technical data on which they will use their judgement in providing an optimised solution. This situation is inevitable since there are certain variables in cost analysis that can be pursued with little hope of meaningful results.

It has always been difficult for individuals with a strongly technical background to accept the lack of precision inherent in certain types of cost estimate. Unfortunately this is sometimes attributed to shortcomings in the Estimators themselves or in the Management information systems that provide the base for cost predictions. There are of course many situations where levels of uncertainty in technical performance, industrial productivity, economic trends etc. are such that they cannot be ignored. So questions as to whether one embarks on a detailed cost analysis or satisfies the requirements by an overall cost assessment qualified by a mature judgement of the underlying uncertainties have to be decided at the outset. These difficulties are a reflection of the fundamental nature of strategic decision making, and in no way detract from the value of detailed LCC analysis as an analytical tool. It merely emphasises the importance of getting into perspective those decision making procedures that can be based on a detailed analysis, and those which cannot.

For instance, in analysing alternative solutions to meet a specific threat a particular option may have a 5% advantage in predicted kill rate. However, if the weapon system is not due into service for 8 years and there is considerable uncertainty as to the nature of the threat that will actually materialise, there may be little point in assigning a notional value to this 5% advantage. Alternatively, in the feasibility stage of specific projects there is certainly considerable scope for undertaking all manners of cost trade-off studies, particularly when absolute costs are of much less importance to the decision making process than relative costs.

For instance, trade-offs concerning reliability, maintainability, availability, quality, vulnerability, interchangeability, etc. are all amenable to intelligent cost analysis. Obviously, these techniques are relevant at later stages in a project although as has been indicated previously a pay back is likely to be less. However, there are certainly effective applications in the operating phase in areas such as crew training, technical facilities and logistic support.

The opportunities for using LCC analysis as a decision making tool appear to be numerous; the key to the successful use of the techniques is in obtaining the optimum mix of numerical analysis and mature judgement.

4.2 Design Parameter

As indicated previously there can be few airframe manufacturers who do not use predicted acquisition and LCC as part of their design procedure. In fact, if there were any, it would be surprising if they managed to survive for any length of time. Where one sees variations in approach this relates mainly to the degree of formality and detail used in setting targets and the procedures followed to achieve those targets.

When one looks for the ideal system, it is necessary to pose the question "Is a formal system required or a mature awareness of the cost drivers?" The answer would depend firstly on the attitude of the national procurement agencies who may wish the Contractor to demonstrate a formal system or may be satisfied that the standard of training provided for Engineers and Designers, the level of cost feedback available within the Company's Management information system and the information on operating costs being fed back from customers, allow optimised designs to be manufactured without the expense and bureaucracy of a formalised system.

Secondly, from the Contractors point of view, it is suggested that the all embracing DTC/LCC system would only be cost effective where there were demonstrable and serious shortcomings in the organising ability to make the necessary cost/technical trade-off at each level of breakdown. This would be particularly relevant to an organisation that has grown extremely rapidly or recently moved into a new type of business when rigid disciplines (with all the cost and programme disadvantages that that implies) are necessary to compensate for the inexperience of the majority of the workforce. No one would seriously argue the importance of using cost as a design parameter; the difficult part is in establishing the degree of formality that must be superimposed on existing systems, and this must also be related to the levels of training, experience and skill of those who commit the organisation to manufacturing costs and the customer to operating costs by the nature of their design.

Whatever the present position of the Contractor or his suppliers, it is clear that there is a current trend towards more formalised systems that not only assist in controlling acquisition cost (DTC) but significantly increase emphasis on downstream costs as well (DTLCC). Some Contractors have recently been working on contracts with built in incentives for achieving reliability and maintainability targets and there is even the possibility of customers requiring reliability and maintainability guarantees. There must be an element of gimmickry in this because of the sheer difficulty in defining tc the mutual satisfaction of all parties whether a target has been achieved or not (e.g. is maintainability to be demonstrated by the superbly trained Contractors team, are equipment failures due to a fault for which the Contractor has liability or due to unusual operational modes).

In moving towards a more rigorous design to LCC system, it is clearly extremely important that Designers and Engineers be supplied with adequate cost/technical information, but without overloading them with detailed information and data of little relevance to their task. As far as the Contractor's staff are concerned, adequate information is usually available to them until the aircraft leaves the factory; after that, he is at the mercy of the customer in terms of useful operational information that is fed back. It is therefore essential that the manufacturers staff develop the personal contacts and understanding of the customers organisation that will ensure a supply of comprehensible cost information to be fed back and assist in the design process, for the next generation of aircraft.

4.3 The Sales/Procurement Aid

In the pressing economic environment where many of our potential customers are in a zero growth situation, the emphasis is still on unit acquisition cost. However, there are few who do not take operating and support costs very seriously. In fact it is unlikely that a winning proposal will emerge that lacks a detailed, well presented and adequately substantiated submission on downstream costs. There are several ways the weapon system supplier may have to approach the requirement and the choice is usually dictated by the customers individual operating procedures. For instance, standard modelling routines can be used, in fact the RCA PRICE suite of models could be a mandatory requirement for certain proposals in the North American Market, in which case the customer would require the input data in order to check the suppliers submission. One's attitude to this approach depends on the understanding of and confidence in any modelling routines to be used. However, in practice everything depends on presenting suitable input data to the model and being able to substantiate the validity of those data.

An alternative approach to sales proposals is to build up a submission analytically, using customer information and manning levels, maintenance procedures, in-country labour rates etc. and possibly assist the potential user in preparing a case for his Government's Treasury Officials. What is clearly evident at the present time is that a weapon system sales proposal is incomplete if not backed up with information on likely operating and support costs, the nature of this being dictated by the detailed customer requirements. The supplier must therefore be prepared to take a very flexible approach to the preparation and presentation of these costs and must not become the slave of a sophisticated cost modelling procedure that is unable to meet the full range of likely customers requirements.

5. QUALITY OF ANALYSES AND HUMAN RESOURCES REQUIRED

The application of LCC analysis in Military Aircraft procurement where there is a requirement to optimise the balance of spend in each phase of a weapon systems life is a difficult and challenging subject. This paper has had to deal very superficially with the subject as a whole, looking at the time in the products life cycle where additional resources should be invested, and the relevance of LCC analysis up to the point where the product is sold. What the layman frequently seems to expect out of these analyses are clear unambiguous statements of predicted cost on which a positive and fully substantiated decision can be made. Life is never that easy and the analysis will never be that good.

However, later papers in this Seminar will indicate in much more detail what is being done in the Warton Division of British Aerospace and will indicate the quality of cost prediction being made. Inevitably there are always problems with the quantity and quality of input data (in particular that being fed back from the customer), it must not be forgotten that data (and in particular high quality data) can be very expensive to obtain, and while there may be few organisations that do not have the need to continually adopt and develop their management information systems to meet the changing requirements, a great deal of money could be wasted in improving the quality of data where no overall cost benefit would accrue.

Probably the most important factor in the successful application of LCC analysis is in the ability of the analysts themselves, by using staff of a very high level of practical experience and analytical ability where they are required to use their specialised numerate skills and their broad knowledge of the business as a whole. If staff are available, one can confidently anticipate analysis and cost summaries of considerably better quality than the input data supplied. It follows that while modelling routines are extremely useful and assist the analysts in many parts of their task, one must have grave reservations about sophisticated unintelligent computerised systems which rely too much on the quality of input data and too little on the ingenuity and skills of the analyst; the use of the intelligent analyst is therefore the key to our overall approach at British Aerospace at Warton where we are making increasingly extensive use of LCC analysis as an additional tool to assist the decision maker to improve the design and to give our potential customers advice in our sales proposal.

REFERENCES

1. The Limits to Growth 1974 - Meadows Pan

2. Evolution of Techniques for LCC Analysis May 1980 - J. M. Jones Agard

NOTE

The views expressed in the paper are those of the author and do not necessarily represent those of British Aerospace.

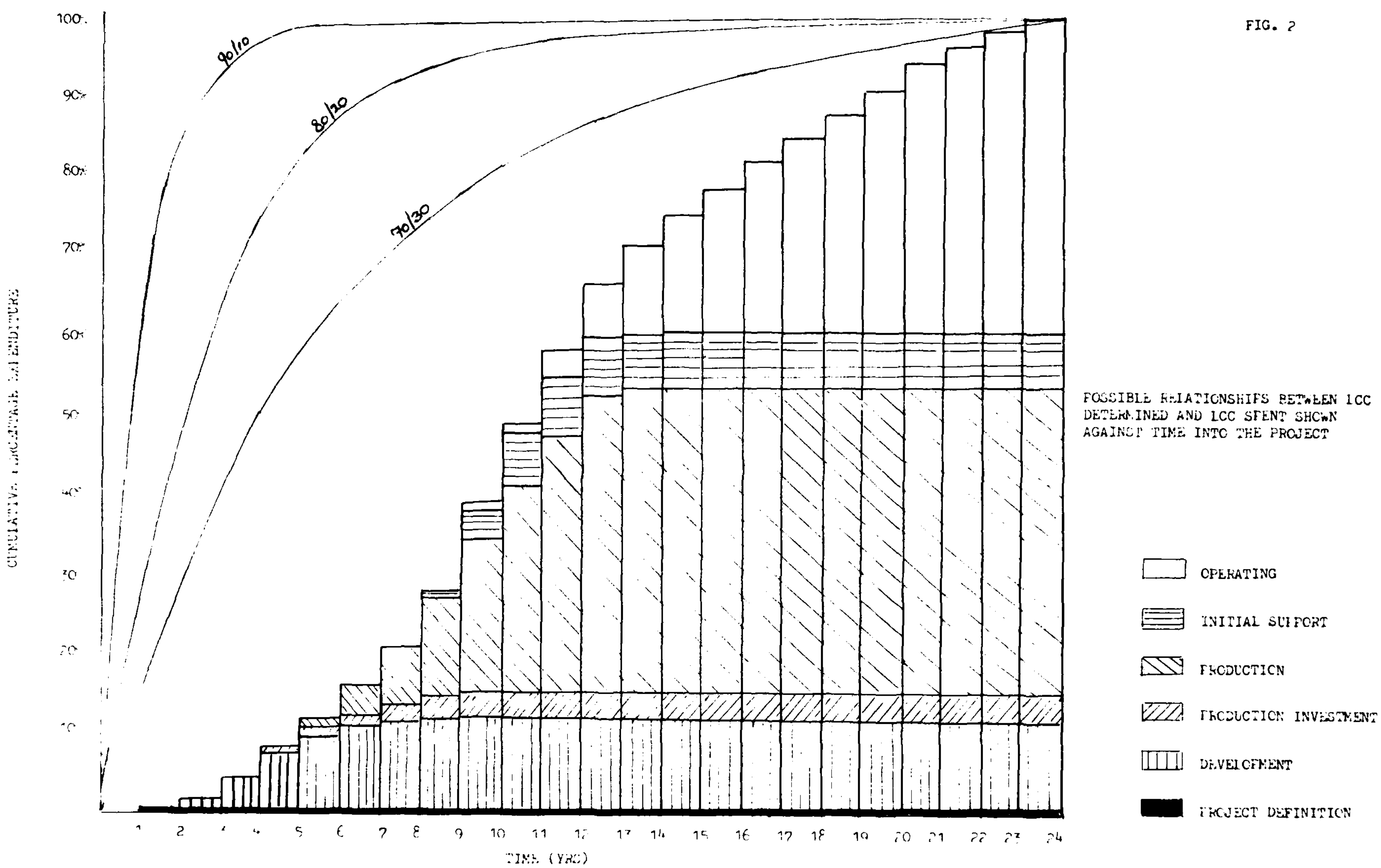
POSSIBLE COST BREAKDOWN FOR 260 MEDIUM WEIGHT TWIN ENGINED COMBAT AIRCRAFT

FIG 1

TIME IN YEARS	T0 1	T1 2	T2 3	T3 4	T4 5	T5 6	T6 7	T7 8	T8 9	T9 10	T10 11	T11 12	T12 13	T13 14	T14 15	T15 16	T16 17	T17 18	T18 19	T19 20	T20 21	T21 22	T22 23	T23 24	T24 TOTAL
PROJECT DEFINITION	5	25																							30
% of Phase	17	83																							
Cum Total	5	30																							
% of Phase Cum Total	17	100																							
% of Project Total	0.1	0.6																							0.7
DEVELOPMENT			72	145	172	109	55	35	22	10															620
% of Phase			11	23	28	17	9	6	4	2															
Cum Total			72	217	389	498	553	588	610	620															
% of Phase Cum Total			11	34	62	79	88	94	98	100															
% of Project Total			1.4	2.8	3.3	2.1	1.0	0.7	0.4	0.2															11.9
PRODUCTION INVESTMENT					20	29	35	33	29	18	10	4	2												180
% of Phase					11	16	20	18	16	10	6	2	1												
Cum Total					20	49	84	117	146	164	174	178	180												
% of Phase Cum Total					11	27	47	65	81	91	97	99	100												
% of Project Total					0.4	0.5	0.7	0.6	0.6	0.3	0.2	0.1	0.0												3.4
PRODUCTION						56	124	185	294	340	344	320	257	74	6										2000
% of Phase						3	6	9	15	17	17	16	13	4	0										
Cum Total						56	180	365	659	999	1343	1663	1920	1994	2000										
% of Phase Cum Total						3	9	18	33	50	67	83	96	100	100										
% of Project Total						1.1	2.4	3.5	5.6	6.5	6.6	6.1	4.9	1.4	0.1										38.2
INITIAL SUPPORT									20	170	150	60													400
% of Phase									5	42	38	15													
Cum Total									20	190	340	400													
% of Phase Cum Total									5	47	85	100													
% of Project Total									0.4	3.3	2.8	1.1													7.6
OPERATING										10	40	114	172	190	188	180	172	170	166	158	150	136	118	36	2000
% of Phase										1	2	6	9	9	9	9	9	8	8	8	7	7	6	2	
Cum Total										10	50	164	336	526	714	894	1066	1236	1402	1560	1710	1846	1964	2000	
% of Phase Cum Total										1	3	9	18	27	36	45	54	62	70	78	85	92	98	100	
% of Project Total										0.2	0.8	2.2	3.3	3.6	3.6	3.4	3.3	3.2	3.2	3.0	2.9	2.6	2.3	0.7	38.2
(1) ANNUAL TOTAL	5	25	72	145	192	194	214	253	365	548	544	498	431	264	194	180	172	170	166	158	150	136	118	36	5230
% of Project Total	0.1	0.5	1.4	2.8	3.7	3.7	4.1	4.8	7.0	10.5	10.4	95	8.2	5.0	3.7	3.4	3.3	3.2	3.2	3.0	2.9	2.6	2.3	0.7	
(2) PROJECT CUMULATIVE TOTAL	5	30	102	247	479	637	847	1100	1465	2013	2557	3055	3486	3750	3944	4124	4296	4466	4632	4790	4040	5076	5194	5230	
PROJECT CUMULATIVE TOTAL %	0.1	0.6	2.0	4.8	8.5	12.2	16.3	21.1	28.1	38.6	49.0	58.5	66.7	71.7	75.4	78.8	82.1	85.3	88.5	91.5	94.4	97.0	99.3	100	

NOTES Costs in £M
Economic conditions 1980

FIG. 2



POSSIBLE RELATIONSHIPS BETWEEN LCC DETERMINED AND LCC SPENT SHOWN AGAINST TIME INTO THE PROJECT

FIG 3

DISTRIBUTION OF INVESTMENT BY PHASE BASED ON 2% COST REDUCTION TARGET

This table is for illustration only, the crude methods used and the gross simplification of cash flows would not be acceptable in a rigorous analysis for investment appraisal purposes.

	(1) Effective year	(2) Life Cycle complete at (1)	(3) Approx. LCC uncommitted 20/80 curve	(4) LCC outstndg.	(5) 50% of outstndg. expend.	(6) LCC Uncommitted	(7) Cost reduction target at 2%	(8) Time to maturity of invest.	(9) Invest. at 10% RR of R	(10) (9) as % of Phase
		%	%	£M	Year	£M	£M	Years	£M	Total
PROJECT DEFINITION	2	8	50	5200	12	2600	52.0	10	20	67
DEVELOPMENT	5	21	20	4791	12	958	19.2	7	9.9	1.6
PRODUCTION INVESTMENT	8	33	8	4130	13	330	6.6	5	4.1	2.3
PRODUCTION	10	42	4	3217	14	129	2.6	4	1.8	0.1
INITIAL SUPPORT	11	46	3	2673	15	80	1.6	4	1.1	0.3
OPERATING	17	71	0.5	934	20	5	0.1	3	0.1	-

COL (1) Incremental investments are assumed to be applied at and effective from the year in which the phase spend reaches 50%

COL (5) Outstanding cash flows are treated as if they occur in the year in which they achieved 50% of their total

COL (8) Investment is assumed to mature after 50% of outstanding LCC has been spent

O&S COST VISIBILITY IN EARLY DESIGN

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SUMMARY

Much has been happening in the last 5 years to improve the capability of the Naval Air Systems Command (NAVAIR) to estimate Operating and Support (O&S) cost. To a large degree, this improvement is due to the appearance in Fiscal Year (FY) 1975 of the first VAMOSC management information system reports. The VAMOSC (Visibility and Management of Operating and Support Cost) MIS (Management Information System) has provided significant visibility into cost differences between aircraft and thus cost differences that are due to a large extent to design, operational, and support characteristics. Early emphasis by the cost estimating community on the use of system level parametric techniques for estimating the O&S costs of new fleet aircraft failed to explain O&S differences in terms of design. The newer data bases have allowed a shift to other methodologies which provide more explicit design related visibility into estimates of O&S costs. This paper focuses on maintenance support costs and related cost data and techniques currently employed by NAVAIR. The paper presents the O&S cost definitions (including the NAVAIR O&S Cost Breakdown Structure (CBS)), data bases, and cost estimating techniques that now allow the analyst to employ engineering oriented cost analysis techniques in early design.

DEFINITIONAL PROBLEMS

Three definitions are pertinent to today's presentation - Life Cycle Cost, which is the total cost to the government of acquisition and ownership of a system over its entire life as defined in DOD Instruction 5000.28; Operating & Support Cost, the cost resulting from operation and maintenance of a system over its operating life; and Maintenance Support Cost, the portion of O&S cost specifically attributable to the maintenance of a system or its equipment. Maintenance support cost includes scheduled and unscheduled labor and material, but it should be noted that the cost of initial support investment is not included. These major categories reflect aggregates of multiple lower level elements of cost.

One of the major problems confronting the cost analyst relates to the definition of these lower level elements. The same cost elements may be defined differently by various Navy data bases. Too often, inappropriate data or methodology are employed simply because the definitions of these data or methodology (in terms of their specific properties) are not sufficiently understood. In other words, the data do not possess the properties needed for their legitimate application to the problem at hand. For example, system level cost data cannot be easily disaggregated to examine the cost implications of design changes at the equipment level.

In order for a data base to be definitionally appropriate to an application it must:

1. be representative of a homogeneous group of systems/subsystems/equipments similar to the one of interest
2. be for systems/subsystems/equipments having similar operating tempo and environment
3. be for systems/subsystems/equipments having similar maintenance and operational philosophy and policies
4. contain actual expenditure data or a very close approximation of same.

The type of problem typically encountered by NAVAIR in its Design-To-Cost (DTC) activity involves

tradeoffs at the equipment level and the ability to relate equipment level differences to system level Life Cycle Cost (LCC). The definitional problems introduced by such a requirement are illustrated in Figure 1. The left side of Figure 1 illustrates a typical weapon system level O&S Cost Breakdown Structure (CBS). The structure is consistent with the DOD Cost Analysis Improvement Group (CAIG), US Air Force, US Army, and US Navy Cost Breakdown Structures (CBSs). The right side illustrates the maintenance support cost breakdown structure that is used in the early design. Though directly linkable, there are maintenance policies and operating concept aspects that must be considered to develop a direct quantitative relationship between the two structures. One such aspect is the "wrench-turning" context of the maintenance support Cost Breakdown Structure (CBS) versus the total manning cost employed in the O&S CBS. For example, if the maintenance man-hour requirements for a system can be reduced through design by the equivalent of one man year per year, it is quite possible that system level manning cost may not be reduced at all. This is especially likely if the savings are spread over a number of subsystems/equipments and affect a number of different skill types in the squadron.

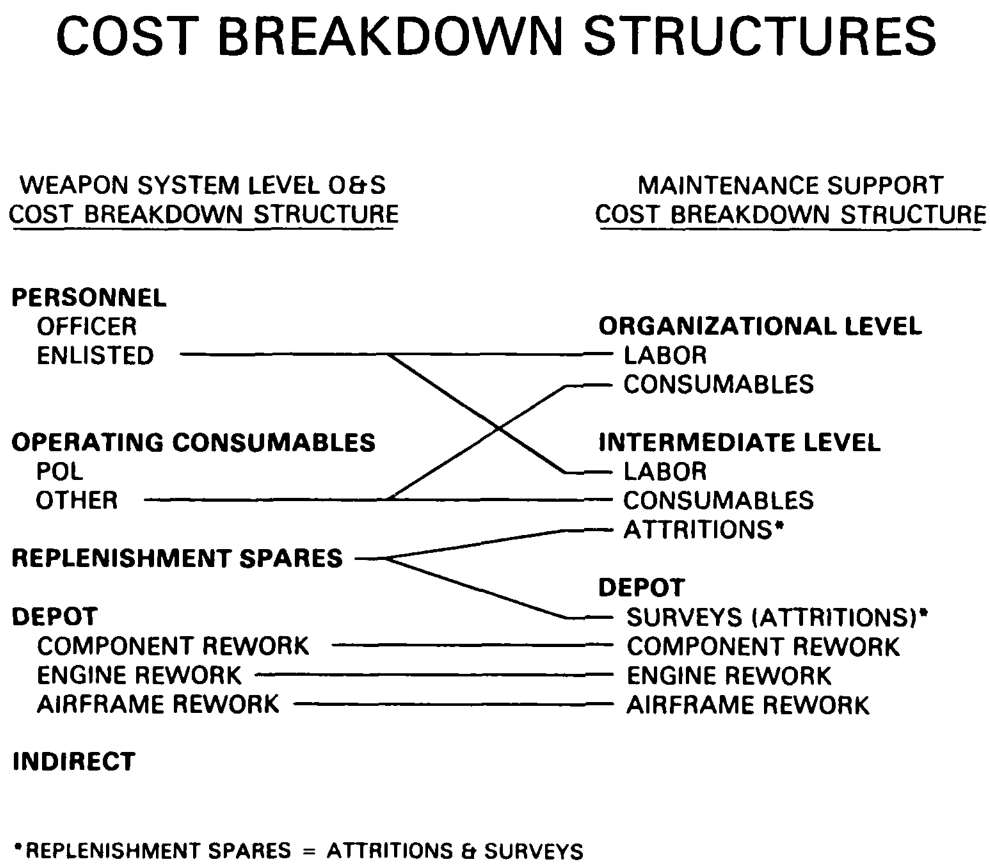

Figure 1

NAVY DATA SOURCES

The most critical aspect of a LCC analysis is the data base that is used to estimate costs for each cost element of the cost breakdown structure. In fact, the data collection system and resultant data base have a tendency to drive the cost breakdown structure. This paper considers two readily available and therefore widely used USN data bases. The older, more established data base is the Navy Resources Model (NARM) and its Navy Program Factors Manual which is sponsored by the Chief of Naval Operations

(OP-901). The newer data base is the Visibility and Management of Support Costs (VAMOSC) System which is sponsored by the Naval Air Systems Command (PMA-270). Both reports provide O&S cost by aircraft Type/Model/Series (T/M/S). However, the VAMOSC report also provides maintenance cost visibility to the 5th digit Work Unit Code (WUC) or "black box" level. By having visibility into the categories of Maintenance Support Cost for existing equipments, an analyst now has the capability to perform creditable trade-offs using design relevant factors.

The NARM data has not been appropriate for detailed design trade-offs for two important reasons. The first reason is the lack of detail available with respect to hardware breakout. The costs are reported at the Type/Model/Series level (e.g., EA-6B, KA-6D, F-14A, etc.). The only exception to this is the depot cost which is broken down by airframe, engine and component reworks. The hardware level of detail is sufficient only for the system level of tradeoff (e.g., F-14 vs VFX). The second reason is that the NARM costs are budget oriented and are based on model generated estimates vice actual data. This is of significant concern in design trade-offs because the degree to which it masks the causal relations between design and cost.

VAMOSC was developed in response to a DOD Management By Objective 3-12 requirement to develop a cost-effective O&S cost management information system. The VAMOSC reports contain data closest in character to actual expenditures, displayed by T/M/S and WUCs, and as a result provide cost estimates in the context required by the program managers concerned with the design decisions. The VAMOSC system produces two reports: the Total Support System (TSS), containing costs at the system level by T/M/S and the Maintenance Subsystem (MS) which contains costs down to the 5 digit WUC level. The TSS is more comprehensive in the inclusion of O&S costs while the MS provides detailed maintenance cost. The VAMOSC TSS report has particular emphasis in the acquisition review process which requires total O&S cost of alternative systems. Managers in the acquisition and design process are visualized as the major users for the detailed information provided by the VAMOSC MS for trade study analysis of alternative equipments. Figure 2 shows a typical VAMOSC MS Report summarized to the 2nd digit WUC level.

The first generation VAMOSC reports were predicated on a requirement that they be based on existing data. These reports are available for four full years plus the transition fiscal year for Navy aircraft.

While the VAMOSC MS provides the designer with a valuable new tool by allowing cost traceability to the subsystem level of a particular Type/Model/Series, it is not a panacea. The Organization & Intermediate (O&I) level maintenance data is based upon the Navy's 3M (Maintenance & Material Management) Reporting System. As a result, the costs are based on 3M Maintenance Action Forms (MAFs), Support Action Forms (SAFs) and Technical Directive Compliance (TDC) forms as reported by Fleet personnel. The VAMOSC MS data is limited by the use of average labor rates which mask the skill levels required for a maintenance action. The data are also based on a sample of reporting squadrons. Though the VAMOSC MS offers an excellent capability to deal with design-related issues, it must be remembered that this report can't be linked directly to total O&S cost. For the same reason, there is a tendency to discredit the manpower cost calculations based on the VAMOSC MS since minor changes in personnel demand generally don't equate to manpower level changes. However, these limitations are not as bad as they might seem, since back-up reports are available which provide detailed information on the reliability and maintainability characteristics that are used to calculate the costs.

SAMPLE MS REPORT

AIRCRAFT = A-7E
TOTAL COMPONENT MAINTENANCE COSTS(IN THOUSANDS OF $)

ORG.LEVEL LABOR RATE = 14.78 PER HOUR
INT.LEVEL LABOR RATE = 14.78 PER HOUR

ALL-NAVY SQUADRONS OCT. 77 - SEPT 78

WORK UNIT CODE	ORGANIZATION MAINTENANCE LABOR SCH	ORGANIZATION MAINTENANCE LABOR UNSCH	ORGANIZATION MAINTENANCE CONSUM SCH	ORGANIZATION MAINTENANCE CONSUM UNSCH	ORGANIZATION SUPPT LABOR	ORGANIZATION TDC LABOR	INTERMEDIATE MAINTENANCE LABOR SCH	INTERMEDIATE MAINTENANCE LABOR UNSCH	INTERMEDIATE MAINTENANCE CONSUM SCH	INTERMEDIATE MAINTENANCE CONSUM UNSCH	INTERMEDIATE SUPPT LABOR	INTERMEDIATE TDC LABOR	INTERMEDIATE ATTR	DEPOT COMPONENT REPAIR NARF O-LAB	DEPOT COMPONENT REPAIR NARF I-LAB	DEPOT COMPONENT REPAIR NARF MAT	DEPOT COMPONENT REPAIR COMMERC LABOR	DEPOT COMPONENT REPAIR COMMERC MAT	DEPOT SURV	DEPOT TDC LABOR	WUC TOTAL COST
03	5110	0	34	0	3206	1	513	0	24	0	43	0	0	13	15	3	75	7	0	0	9044
11	935	1316	187	836	1240	16	11	323	1	31	29	10	148	113	163	53	3	0	28	25	5527
12	45	362	30	295	147	51	2	33	2	41	15	2	14	23	37	58	94	0	41	0	1302
13	150	1329	185	993	514	81	31	505	9	172	98	4	489	345	504	345	152	12	580	0	6506
14	231	1156	38	236	323	67	20	142	18	150	27	1	455	209	284	556	0	0	223	0	4156
23	295	1197	14	136	164	4	768	230	133	35	484	12	11	11	15	15	1068	104	123	0	4794
27	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
29	18	379	7	62	121	1	1	90	1	33	0	0	3	61	88	80	58	0	202	0	1222
41	21	418	21	237	109	4	3	80	1	53	17	1	37	146	207	949	337	30	96	0	2768
42	33	944	27	374	249	23	2	125	1	25	17	0	16	122	184	159	40	4	34	0	2382
44	15	306	15	248	110	3	3	120	1	23	7	0	57	6	9	8	0	0	7	1	939
45	43	395	22	155	163	12	4	45	6	68	13	0	31	71	101	164	0	0	63	0	1366
46	32	617	17	261	155	25	6	123	1	18	75	0	16	89	139	93	370	41	77	3	2173
47	2	17	1	18	25	7	1	35	0	8	22	0	7	11	16	28	35	3	79	0	333
49	15	152	5	56	47	1	4	9	0	1	4	0	30	24	33	50	0	0	20	0	431
51	10	721	9	142	194	42	3	163	2	68	10	5	83	274	400	200	277	29	24	12	2696
55	3	56	2	21	32	6	1	9	0	0	1	0	0	8	12	11	14	1	0	0	177
57	14	730	3	74	129	9	6	432	2	220	17	0	18	319	534	326	0	0	170	0	2974
63	15	449	5	90	374	2	14	475	2	60	11	0	4	26	41	16	181	33	15	0	1803
64	2	23	0	0	15	0	0	6	0	2	1	0	0	0	0	0	1	0	0	0	49
65	4	117	7	282	93	1	4	146	1	50	4	0	2	4	6	7	13	1	1	0	744
66	0	2	0	13	2	2	0	1	0	0	1	0	2	0	0	1	8	0	0	0	24
67	1	23	0	2	24	0	0	12	0	14	1	0	2	3	5	2	0	0	2	0	91
69	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
71	20	495	7	124	445	6	7	489	4	212	13	7	7	55	96	66	272	24	20	0	2548
72	19	245	6	37	170	2	10	148	12	50	5	0	18	56	78	77	195	18	53	0	1259
73	83	2400	22	347	3313	12	248	2785	56	1195	53	0	307	496	693	1007	2622	242	274	0	16155
74	17	294	9	77	485	7	6	153	1	34	7	5	9	24	37	15	69	6	23	0	1276
75	134	482	13	147	1107	7	196	168	2	27	16	11	39	204	781	258	585	52	152	0	4082
76	15	373	12	141	198	5	5	382	3	232	11	9	44	63	88	109	219	26	85	0	2025
77	2	16	5	20	17	1	0	1	0	0	1	0	0	0	0	0	13	2	0	0	76
91	6	25	8	65	28	1	1	7	0	7	48	1	80	13	17	30	0	0	11	0	347
93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
96	0	3	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	6
97	2	35	0	3	12	10	0	0	0	0	1	1	0	0	0	0	0	0	0	0	65
TOTAL	7379	15105	788	5508	13412	409	1869	7268	290	2830	1859	73	1929	12788	4048	4693	6692	654	2402	47	79165

PRE-EX MAT	4404
UNALLOC ORG SUPPT LAB	15541
ORG TDC MAT	4
INT TDC MAT	1
DEP TDC MAT	0
GRAND TOTAL FOR A-7E	99115

Figure 2

COST ESTIMATING APPROACHES

The four general cost estimating approaches are shown in Figure 3. The most common is the statistical parametric technique which develops trends from existing data bases to predict nominal costs. The next technique employs analogies. This approach is useful when data obtained from field experience is adjusted (scaled) for differences in design or operational environment. Engineering buildup techniques provide the most detailed methodology and are based on engineering-oriented data such as demand and consumption relationships, repair time functions, etc. Using any of the above techniques, a "bench-mark" system experience basis is utilized to estimate the comparable cost of a proposed system.

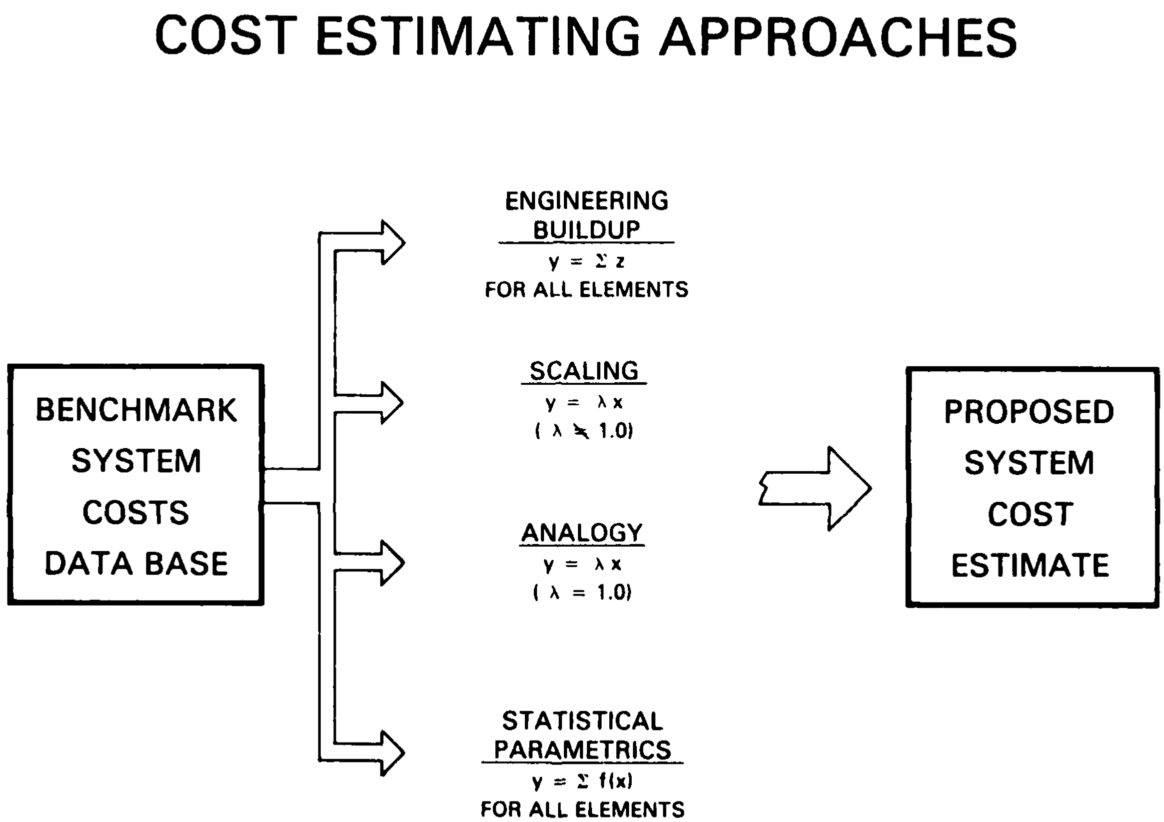

Figure 3

Figure 3 also indicates the hierarchy that exists between these costing techniques, established in terms of their usefulness in design tradeoff studies. Statistical parametrics rank at the lower end of the spectrum, with engineering buildup providing the highest level of design visibility. The advantages and disadvantages of each technique are discussed below:

Statistical Parametrics: While useful for setting nominal values for independent costing, it is generally ineffective for use in design trade-off studies. Another problem with this approach is its potential for misuse because it appears to be so flexible. It is easy to unknowingly extrapolate outside of the similar functional hardware data base that was used to generate the statistics.

Scaling: Scaling for system differences is the most practical approach in design trade-offs when linked with analogy. To be effectively used however, technology must be basically stable and some insight into significant design differences is required.

Analogy: Analogy is essentially scaling where the scaling factor can be established as unity. It offers a high level of credibility because it represents actual field experience from an equivalent system. However, as a result, it has limited direct application since few items are used as is.

Engineering Buildup: While engineering buildup offers the highest level of design visibility, it is not usually practical in the early design because so much design detail is required and not generally available. In addition, there is a high risk of not considering all of the impacts.

As a result of the strengths and weaknesses of each approach, scaling has been selected as the primary costing technique to illustrate the capabilities provided by the recent data base innovations. The primary reason for this selection is that scaling factors, when applied to analogous equipment, can provide the highest costing credibility during early design because it provides a causal basis between design drivers of cost and the cost estimate. The credibility comes particularly from the designer recognizing that specific actions which he controls also logically affect the cost. A significant point that can be made here is that the scaling techiques have another benefit; that is, they can be applied at any level of hardware indenture, if data exists, and that they generally act like a catalyst. They modify the inputs but do not themselves mask the relationship between input and output. In addition, not as much data is required for the existing systems as is required when using statistical techniques.

In all cases, experience has shown that even though techniques make sense, subtle data or methodology problems can result in significant errors or output inconsistencies, particularly when the total is the summation of a large number of elements of cost. Use of these scaling techniques, as in any costing approach, requires that the analyst consider the results and ask whether the results make sense. However the estimate is made, it is always good practice to perform an independent check on the estimate and its elements.

CASE EXAMPLE

There is no implication that this example is the only way to estimate or develop the scaling factors. In fact, some efforts by NAVAIR are indicating that nonlinear techniques to develop scaling factors would provide a significantly improved estimate. The guidance for selecting the technique to develop the scaling factors and estimates for any specific case must, of course, come by detailed analysis and understanding of the data bases and the design differences.

In this example, all estimated costs are based on VAMOSC MS data. First, a baseline subsystem that is analogous to the new subsystem must be selected. Extraction of maintenance labor and consumables from the VAMOSC MS provides the data that are then scaled by a labor (usually man-hour) scalar and a materials scalar. The labor scalar developed will usually be reflective of the parameters that drive manpower, such as demand or repair time, while material scalars will reflect parameters that are driven by demand and cost oriented factors. All of these factors are available to varying levels as predictions in the early design phase of a program.

Figure 4 presents sample FY-78 costs from the VAMOSC MS report. The costs are on a cost per flight hour ($/FH) basis for the S-3A, A-6E, F-4J, EC-130Q, and A-7E Radar Sets. These data provide a good degree of visibility into maintenance cost drivers and, at the lower WUC level provided by VAMOSC MS,

allow the cost analyst to identify cost drivers for existing systems. As a result, he may focus his attention on those cost drivers for the new system as it is being designed.

COST PER FLIGHT HOUR, RADAR SETS; FY-80$

Cost Element	T/M/S; FY-80$/FH					
	S-3A	A-6E	F-4J	EC-130Q	A-7E	New Radar System
'O' Level						
Labor	$ 2.66	$ .58	$12.07	$1.66	$ 5.63	$ 4.77
Consumables	.35	.27	.78	.37	1.11	.94
'I' Level						
Labor	3.61	1.72	7.24	2.21	5.74	7.31
Consumables	5.29	2.09	4.92	2.41	2.16	2.69
Attritions	.48	1.88	.21	.00	1.36	2.08
Depot Level						
Comp Rwk	13.52	2.62	22.72	1.20	6.17	7.01
Surveys	.00	.00	.57	.00	.53	.81
Total	$25.91	$9.16	$48.51	$7.85	$22.70	$25.60

Radar Sets:		
	S-3A	AN/APS - 116
	A-6E	AN/APQ - 92
	F-4J	AN/APG - 59
	EC-130Q	AN/APN - 59
	A-7E	AN/APQ - 126

Figure 4

Figure 5 provides the 5 digit work unit code (WUC) breakdown used for this example with the component nomenclature. Note that four components (high cost drivers) are broken out explicitly and all other components are aggregated into one value (73A1X). The technique employed for this example separates, on a maintenance action per flight hour (MA/FH) basis, those actions which are design related versus those which are environmentally related. Thus, only a proportion of the baseline value is scaled by the change in maintenance action rate, while the remainder of the cost is carried through. This technique, demonstrated in Figure 5, also provides for more system specific field-type data derating by identifying the environmentally related maintenance actions for that type equipment. Figure 6 contains the direct maintenance manhours per flight hour (DMMH/FH) labor scalar derivation.

Figure 7 shows the development of scalars which are applied to the baseline costs to arrive at estimated costs for the hypothetical subsystem. The unit cost estimates for the new subsystem are based on contractor data. These estimates will show cost differences in the 5 digit aggregation of components. As indicated earlier, the values and parameters used to develop the scalars are intended to be indicative only of the approach. In order to be credibly applied, the scaling technique must be supported by effective technical evaluation of the design which determines the significant cost drivers. Particularly in early design, where the parameters levels are questionable, sensitivity

analyses should be performed to determine a credible range of variation in the scalar values and therefore to establish a range of variation in the estimated costs. This, in fact, might provide a useful technique to expose cost risk variations.

DEVELOPMENT OF EXPECTED NAVY ENVIRONMENT MAINTAINABILITY AND RELIABILITY FACTORS FOR NEW RADAR SYSTEM

WUC*	Baseline Radar System MA/FH	Avionics Reliability Scalar**	Environment Induced MA/FH	Contractor Estimate New Radar System MA/FH	Navy Expected New Radar System MA/FH
	(1)	(2)	(1) x (2) (3)	(4)	(3) + (4) (5)
73A11	.0186	.37	.0069	.0080	.0149
73A12	.0106	.37	.0039	.0066	.0105
73A13	.0138	.37	.0051	.0070	.0121
73A15	.0236	.37	.0087	.0110	.0197
73A1X	.0157	.37	.0058	.0091	.0149
MFHBUMA	12.15	-	-	-	13.87

WUC	Baseline Radar System Failures/FH	Avionics Reliability Scalar*	Environment Induced Failure/FH	Contractor Estimate New Radar System Failure/FH	Navy Expected New Radar System Failure/FH
	(1)	(2)	(1) x (2) (3)	(4)	(3) + (4) (5)
73A11	.0103	.37	.0038	.0055	.0093
73A12	.0056	.37	.0021	.0032	.0053
73A13	.0078	.37	.0029	.0050	.0079
73A15	.0115	.37	.0043	.0042	.0085
73A1X	.0086	.37	.0032	.0047	.0079
MHFBF	22.83	-	-	-	25.71

NOTES:*

NOTES:*	73A1	AN/APQ Radar Set
	73A11	Receiver Antenna
	73A12	Radar Transmitter
	73A13	Program Power Supply
	73A15	Command Computer/Multiple Indicator
	73A1X	All Other Components

**The 37% scalar is a percentage of non-design-controllable maintenance actions as determined from the "Aircraft Maintenance Experience Design Handbook", Vought Corp., Dallas, Texas, September 1978.

Figure 5

DEVELOPMENT OF RADAR ORGANIZATIONAL & INTERMEDIATE LABOR SCALARS

Maintenance Level	Historical Navy DMMH/FH	Estimate of New Navy DMMH/FH	Labor Scalar
	(1)	(2)	(2)/(1) (3)
O Level DMMH/FH	.40	.34	.847
I Level DMMH/FH	.36	.46	1.274
Total	.76	.80	

Figure 6

DEVELOPMENT OF RADAR UNIT COST SCALARS

WUC	Historical Navy Radar Cost*	Estimate of New Navy Radar Cost*	Unit Cost Scalar
	(1)	(2)	(2)/(1) (3)
73A11	$45 K	$75 K	1.67
73A12	$20 K	$35 K	1.75
73A13	$30 K	$60 K	2.00
73A15	$40 K	$35 K	.87
73A1X	$15 K	$45 K	3.00

*All costs are in Fiscal Year 80 $.

Figure 7

For the purposes of this example, the baseline and hypothetical equipment were divided into major component groupings. The VAMOSC MS cost data were then normalized on a cost per maintenance action or per failure basis for the baseline equipments component groupings. The results of applying this approach to the specific example are shown in the following figures. Historical data for the baseline equipment is presented at the Organizational, the Intermediate, and the Depot level. In this case, the Organizational and Intermediate level labor costs are considered a function of DMMH/FH (Figure 8). Organizational level consumables (Figure 9) are a function of maintenance actions while Intermediate level consumables (Figure 9), component rework material (Figure 10), and replenishment spares (Figure 11) are a function of failures and unit cost. Depot labor for component rework is scaled by the failure rate and anticipated man-hour requirements for a depot repair, and includes indirect labor. The material portion is scaled by the failure rate and unit cost. The resultant cost estimate for the hypothetical equipment can now be determined and evaluated in comparison with those listed in Figure 4.

DEVELOPMENT OF NORMALIZED O&S COST
ESTIMATE FOR NEW RADAR SYSTEM -- FY-80 $

------------O&I Level Labor Cost------------

	Baseline Radar Systems $/FH	Labor Scalar	New Radar $/FH
O Level Labor	5.63	.847	4.77
I Level Labor	5.74	1.274	7.31

Figure 8

DEVELOPMENT OF NORMALIZED O&S COST
ESTIMATE FOR NEW RADAR SYSTEM -- FY-80 $

	O Level Consumables			I Level Consumables			
WUC	Baseline $/MA	New Radar System MA/FH	New Radar System $/FH	Baseline $/Failure	New Radar System Failures/FH	Unit Cost Scalar	New Radar System $/FH
	(1)	(2)	(1)x(2) (3)	(4)	(5)	(6)	(4)x(5)x(6) (7)
73A11	$20.55	.0149	$.31	$53.77	.0093	1.67	$ .84
73A12	$ 4.10	.0105	$.04	$27.70	.0053	1.75	$ .26
73A13	$ 1.58	.0121	$.02	$26.74	.0079	2.00	$ .42
73A15	$18.59	.0197	$.37	$92.99	.0085	.87	$ .69
73A1X	$13.47	.0149	$.20	$20.11	.0079	3.00	$ .48

"O" Level Consumables - $.94/FH "I" Level Consumables - $2.69/FH

Figure 9

DEVELOPMENT OF NORMALIZED O&S COST
ESTIMATE FOR NEW RADAR SYSTEM -- FY-80 $

	COMPONENT REWORK						
	Baseline Material Cost $/Failure	Unit Cost Scalar	Baseline Scaled Material Cost $/Failure	Baseline Labor Cost $/Failure	Baseline Total Cost $/Failure	New Radar System Failures/FH	New Radar System $/FH
	(1)	(2)	(1)x(2) (3)	(4)	(3)+(4) (5)	(6)	(5)x(6) (7)
73A11	$110.91	1.67	$185.22	$119.89	$305.11	.0093	$2.84
73A12	$117.52	1.75	$205.66	$ 85.76	$291.42	.0053	$1.54
73A13	$ 8.14	2.00	$ 16.28	$ 29.52	$ 45.80	.0079	$ .36
73A15	$ 82.96	.87	$ 72.18	$ 60.13	$132.31	.0085	$1.13
73A1X	$ 30.68	3.00	$ 92.04	$ 51.99	$144.03	.0079	$1.14

Component Rework $7.01/FH

Figure 10

DEVELOPMENT OF NORMALIZED O&S COST
ESTIMATE FOR NEW RADAR SYSTEM -- FY-80 $

	REPLENISHMENT SPARES			
WUC	Baseline $/Failure	New Radar System Failures/FH	Unit Cost Scalar	New Radar System $/FH
	(1)	(2)	(3)	(1)x(2)x(3) (4)
73A11	$ 53.22	.0093	1.67	$ .83
73A12	$ 26.18	.0053	1.75	$ .24
73A13	$ 63.02	.0079	2.00	$ .99
73A15	$ 42.95	.0085	.87	$ .32
73A1X	$ 21.73	.0079	3.00	$ .51

Replenishment Spares $2.89/FH

Figure 11

CONCLUSIONS

With the increased use of VAMOSC data, more accurate cost predictions are now possible. Those data can be used for design tradeoffs, integrated logistic support planning and program reviews, to mention a few. There are some problems with the data bases. Some inconsistencies and data anomalies are only partially identified. From the depot level it is difficult to trace an equipment to a particular Type/Model/Series. The significant point to be discerned is that the differences do not disqualify the use of any of these data bases. Rather, the cost analyst must understand the characteristics, definitions, and data sources and their meanings. Knowing these, the analyst is armed with a significantly improved basis for being responsive to a wide range of estimating requirements. Despite some unresolved problems, we are still ahead of where we were even five years ago. At that point in time, we couldn't hope to address these design problems using field data. We had data then, but couldn't determine what it contained. Because of the new highly visible data, we are now able to deal more effectively with design issues as they arise. The key is to perceive the needs of the acquisition review process and the design process. The important requirement in early design is to know the impact of a design alternative to allow management to make more realistic decisions. We must capture the cost reduction opportunities before the design freezes.

NAVAIR work is not done by a longshot. The current NAVAIR focus is on greater data base research, improvement in cost estimating techniques, and better applications of this new data base. In conclusion, the use of VAMOSC data hopefully will lead to a better quality of cost tracking and cost estimation at all levels of repair and for all types of equipment.

U.S. Army Design-to-Cost Experience

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ABSTRACT

Design-to-Cost procedures have been included in all major U.S. Army aviation procurements since 1972. Experience has been gained during design, development, procurement and initial fielding of several major systems. The ownership cost of this equipment is considered during development, production and operational phases, and techniques for cost control are discussed. Lessons learned as a result of joint Government-Industry Design-To-Unit-Production-Cost programs are presented. Techniques which have been effective in cost management on utility and attack helicopters and turbine engine programs are listed. Producibility engineering planning, initial production tooling, and facilitization to reduce production costs are discussed. The role of warranties in controlling operating and support costs is illustrated. It is concluded that Design-To-Unit-Production-Cost techniques have been effective in achieving lower production costs, but that additional work is necessary to better control operating and support costs and thereby achieve optimal life cycle costs.

INTRODUCTION

Design-to-Cost

The U.S. Department of Defense (DOD) introduced the Design-to-Cost (DTC) concept in 1971 when it concluded that, in view of budget limitations and rising cost of weapons, it might be more realistic to design weapons with greater consideration to what it could reasonably afford to pay for them. This gave rise to the term "Design-to-Cost" (or Design-to-Price). The following paragraph states DOD's policy on this concept:

> Cost parameters shall be established which consider the cost of acquisition and ownership; discrete cost elements (e.g., unit production cost, operating and support cost) shall be translated into "design to" requirements. System development shall be continuously evaluated against these requirements with the same rigor as that applied to technical system capability, cost and schedule. Traceability of estimates and costing factors, including those for economic escalation, shall be maintained.

The Design-to-Cost concept has been applied to a number of U.S. Army aircraft programs for several years. Ideally, each of these programs had reasonably firm DTC goals before contracting, large projected production runs, early consideration of life-cycle cost, moderate anticipated technological risks, and some contractor competition. These conditions made the programs good candidates for successful application of the Design-to-Cost concept.

This concept begins with a determination of how much the U.S. Army can pay to acquire and operate a new piece of equipment. In light of these constraints, desired bands of performance and features are established that will be acceptable to the "user." Within these parameters the design engineers then arrive at the optimum solution based on iterated trade-off studies. The principal purpose of DTC is to encourage designers to achieve lowest manufacturing costs by making trade-offs between cost and other design factors. Adherence to DTC discipline gives designers at all levels the authority to conduct system performance/cost trade-offs on component design, development and manufacturing processes. Potential cost advantages of emerging materials and processes are frequently embraced, thus accelerating technology transfer.

With the award of production contracts on the Utility Tactical Transport Aircraft System (UH-60A UTTAS) and the T-700 gas turbine engine, the U.S. Army achieved its first major experience in aviation systems Design-to-Cost management. That experience is being applied in a variety of developing systems including the medium lift (CH-47D) modernization program, the Advanced Attack Helicopter (AAH) with its Target Acquisition Designation System/Pilot Night Vision System (TADS/PNVS) components, and the Remotely Piloted Vehicle (RPV). Current and forecast aviation DTC procurements will total more than $8 billion by Fiscal Year 1985.

Operating and Support Cost

In addition to these procurements shown in Figure 1, considerable emphasis is being placed on the operational suitability of these systems. Techniques such as Reliability, Availability and Maintainability (RAM) goals and Reliability Improvement Warranties (RIW) are being employed to insure that the equipment procured at the best possible price will also have affordable ownership costs. Inclusion of these processes in the design phase is of equal importance with the Design-to-Cost discipline.

Life Cycle Cost

Life Cycle Cost (LCC) is the sum of all components shown in Figure 2. Representative magnitudes of these components are depicted in Figure 3. The cost management strategy presently applied in U.S. Army Aviation is to invest adequate funds during the full scale

engineering development phase to insure DTC and reliability management; to emphasize establishment and achievement of realistic unit procurement goals; and to consider Operating and Support (O&S) cost drivers both during development and fielding. Although primary emphasis is typically placed on investment costs, it is recognized that one cannot design for low procurement cost such that O&S costs are degraded. Conversely, the immediacy and visibility of the procurement process prohibits excessive investment costs solely to minimize O&S costs. Design-to-Cost is thus a management concept wherein rigorous cost goals are established during development and the control of systems cost (acquisition, operating, and support) to these goals is achieved by practical trade-offs between operational capability, performance, cost and schedule. Cost, as a key design parameter, is addressed on a continuing basis and is an inherent part of the development and production process.

Until the advent of DTC, designing to minimize costs was a secondary consideration. Other requirements, such as performance, structural integrity, durability, and weight took precedence over cost. Too often, cost trades were made if and when the drawing release schedules permitted them. Fabrication of the Black Hawk in modules is an example of lowering manufacturing cost by "thoughtful" design while retaining all the other essential system characteristics. During the early design stage--when requirements were closely examined to insure that the final product would meet its objectives, this approach was identified as the most cost effective. Each of the modules is substantially fitted out with its hydraulics, electronics, flight controls, and other equipment before attachment to adjacent sections. This allows the work to be performed within the reach of the most efficient equipment and with the most efficient use of manpower. Had this decision been delayed until commencement of fabrication, the efforts to reduce cost would have lost their impact because design changes then cost more than the savings that result.

In the AAH Program, formation of a broadly based subcontractor team, each bring specialized capabilities and facilities proved to be an effective means of minimizing facilitization costs and optimizing manufacturing and engineering manpower. Again if this decision had been made following the detailed design phase, much of the cost benefits would have been lost.

DEVELOPMENT PROCESS

Army-Industry Teamwork

U.S. Army development of major aircraft systems is a joint effort between government and industry. The Army defines systems performance, schedule, and cost requirements, establishes contractual specifications, encompassing design standards, development activities, qualification requirements and acceptance criteria; and performs contractual cost, schedule, and system performance management activities.

The role of the contractor in DTC is crucial because he is the one ultimately doing the "design" work. Making cost a primary design objective cannot be accomplished without a contractor's commitment. Keeping score costs money and makes no contribution unless astute management and key engineering talent are committed to bringing the system into production at or under the targets originally established for the program. A responsive DTC reporting system must provide the cost visibility to the engineering decision-makers so they can maintain control of the design's key cost parameters. Sustained visibility on costs will almost always require further analysis and innovation from design, purchasing, and manufacturing engineering groups. Each high cost item must be studied in cost and technical depth to: (1) update obsolete items, (2) remove unnecessary features, (3) simplify high cost features, and (4) improve operational readiness, reliability and maintainability.

Cost Program Management

The characteristics of successful Army/contractor cost program management are listed below:

1. There are clearly defined organizational responsibilities for system cost management including Design-to-Cost and Life Cycle Cost.

2. Cost drivers are identified and tracked for at least 80 percent of total estimated production and ownership costs. The "paper design" must achieve established cost goals before the hardware design is started.

3. Cost estimating methods used by the contractor are sound, based upon his prior experience for similar work, and can be validated by qualified Government cost analysts and engineers. Government feedback is important.

4. Priorities among design requirements are defined and trade-off studies made on a continuing basis. Design iterations for cost reductions are an inherent part of an effective program.

5. Estimated production and ownership costs are distributed down to a level that represents specific targets for individual design groups who are accountable for their achievement.

6. Design-to-Cost reports generated for contractor internal use are summarized for customer, program managers and corporate top management, reviewed by the contractor and Government and fed back to the designer.

7. Close attention is paid to producibility costs; and tooling and manufacturing managers participate throughout the design process.

8. Comparable attention is paid to subcontract DTC and LCC performance.

Figure 4 emphasizes the vital importance of DTC activity. In terms of cumulative systems investment cost, less than five percent is typically expended by the completion of the advanced development phase and substantial cost savings are possible. The savings potential diminishes rapidly as the detailed design is completed and configurations are frozen. While value engineering savings are possible during the production phase, these must be sufficiently cost effective to pay back the cost of re-engineering, requalification, retooling and sometimes retrofitting.

In order to insure industry's attention to DTC objectives, a number of strategies are employed. Typically, a non-negotiable Design-To-Unit-Production-Cost (DTUPC) is introduced as a contract requirement and tracking systems; allocation of costs to assemblies, sub-assemblies and components; monthly reports, annual formal reviews and independent audits are utilized to manage the process. It is interesting to note that the UTTAS was evaluated as being on DTUPC target in 1972, 1973 and 1974, and grew by only ten percent at the time of the production award in 1976.

DTUPC Award Fee

To further stimulate effective cost management, the U.S Army has recently included DTUPC award fee clauses in development contracts. The fee is typically divided into increments payable annually based on the Government's review and assessment of the contractor's DTC management and results. In the first several increments partial fees can be won by evidence of management commitment, established procedures, and formalized reporting and feedback. Award of the entire fee is generally dependent upon success in meeting DTC objectives.

In a sole source environment it may be very desirable to utilize the DTC award fee although it can be argued that industry views fee income as being only a minor incentive as compared to production profit. In a competitive development environment, DTC award fees may be used to introduce cost management to "new offerors" but will probably not play a major role in the success or failure of a given effort.

One must be very careful not to introduce conflicting signals during development. This was unwittingly done in the maturity phase of the UTTAS program where extremely attractive performance incentives were combined with DTC award fees. The performance incentives clearly motivated the contractor to undertake significant redesign and requalification at Government expense due to the cost type contract in order to achieve unprecedented weight reduction and performance gains. The contractor also asserted that attainment of cost reduction was a foremost consideration for every redesign item. However, many of the high cost components of the UTTAS were not subjected to the redesign process.

Contract Requirements

The Request for Proposal (RFP) should request the offeror to propose a Design-to-Cost approach compatible with the contractual Statement of Work (SOW). All of the DTC/LCC requirements are documented in the SOW. The contractor documents how he will implement these requirements in a DTC/LCC program plan. The DTC approach should establish Life Cycle Cost as a parameter to be considered equally with technical requirements and schedule throughout the design, development, production and deployment of the program. The offeror's approach should provide the following:

Internal Controls.

a. Establishing goals and subgoals and suballocations of these goals at various management levels down to the engineering group responsible for a specific cost account.

b. Providing incentives to meet or better assigned subgoals.

c. Identifying those hardware/software items and program tasks which have a dominant effect on the total LCC.

d. Establishing and maintaining the logistics support cost "drivers" data file with supporting input parameter rationale. The data in this file must be consistent with the data contained in the Integrated Logistics Data File, the Failure Modes and Effects Analysis, Logistics Support Analysis, and Spares Provisioning process.

e. Incorporating DTC requirements in design subcontracts.

Life Cycle Cost Trade Studies.

a. Identifying and prioritizing potential LCC reductions.

b. Identifying new study candidate items.

c. Implementing the LCC trade study effort.

Status Assessment and Reporting.

a. Determining and tracking the DTC status.

b. Reconciling the DTC estimates with the Cost Schedule Control System Criteria (C/SCSC) or other cost management and logistics data systems.

c. Identifying, documenting and tracking design decisions made to reduce the LCC.

d. Providing a high degree of government and contractor visibility into LCC activities.

e. Providing timely support to Army program validation reviews. (The Army must provide feedback as well.)

Integration.

a. Providing information and incentives to each organization level to consider LCC on an equal basis with technical requirements and schedule.

b. Providing a cross-reference between the Work Breakdown Structure (WBS) and the Work Unit Cost (WUC).

Engineering Change Proposal/Value Engineering Change Proposal (ECP/VECP) Analysis.

The contract should specifically state that all Engineering Change Proposals (ECPs) will require an analysis of how the proposed change affects the Design-to-Cost goals and Life Cycle Cost of the program.

UTTAS Program

In mid 1972, Boeing-Vertol and Sikorsky were each awarded airframe development contracts with Design-To-Unit-Production-Cost targets. The Special Provisions section of the contract schedule provided an established average recurring airframe cost of $600,000 (constant FY 72 dollars). The contract Design-to-Cost incentive was provided by an increase in contract fee by 15 percent of the difference between the average airframe production cost and the airframe cost objective of $600,000 multiplied by the number of total aircraft to be produced in the first production contract. If the amount negotiated for the average airframe cost was below $550,000, 20 percent would be used in lieu of 15 percent above. Conversely, the DTC penalty of going above $600,000 would be a reduction of fee amounting to 15 percent of the difference multiplied by the number of aircraft to be procured on the first production contract. Minimum and maximum fee limitations were established in Section E of the contract. The fee structure is illustrated in Figure 5.

The determination of the average airframe cost for DTUPC incentive fee on 1107 airframes was based on the negotiated average cost of the first production contract for 15 aircraft. An 85 percent learning curve was used to project the cost of 1107 airframes. This value was adjusted to FY 72 constant dollars using the latest Gross National Product inflation rate. The resultant average was then compared to the DTUPC goal of $600,000.

Design-To-Unit-Production-Cost was tracked at bi-monthly executive sessions between the contractor and the procurement team to add a management and control dimension to the project. The contractor was allowed to make changes without government approval provided he did not degrade the system performance below the following levels:

Characteristic	Criteria
Cruise speed	145-175 kts
Vertical flight performance	450-550 ft/min
Endurance	2.3 hrs
Payload	11 troops/2640 lbs

By specifying bands, the Army indicated to bidders that it expected trade-offs.

AAH Program

In the AAH RFP in late 1972, the Army explicitly defined a requirement in which cost was of equal priority to technical performance, and which identified a maximum allowable flyaway cost of $1.6 million (constant FY 72 dollars). The program goal, as modified by OSD-directed/approved changes, is still the goal today, and should be met. The offerors and the selected contractors were allowed to make changes without Government approval provided they did not degrade payload/endurance minimums; cruise speed of 145-175 kts; or vertical rate of climb of 450-550 ft/min. By specifying bands of performance, the Army indicated that it expected trade-offs, since historically offerors have tended to read more capability into the specification than the Army needed.

The AAH DTC program is unique, in that it contains all subsystems in the AAH, including all armament/fire control and Government-Furnished Equipment, as well as the TADS/PNVS, as shown in Figure 6. The program is also unique in that a significant percentage of the system is manufactured by Hughes' major subcontractor team, and hence requires a coordinated approach to DTC activities.

The DTC is tracked by Hughes on a continuing basis, with monthly reports to the Army and an annual DTC review by an Army team. Team members in the appropriate specialized disciplines also conduct these reviews with Hughes at all major subcontractors. The results of the reviews are compiled in current dollars, and are deflated to FY 72 dollars based on a composite material price/aircraft worker wage index. By this means the economic fluctuations within the aircraft arena are considered in the current estimate. The results of the reviews are also discussed (including the Army's estimates) with both Hughes and the subcontractors, providing much-desired feedback to the manufacturer as well as a forum for identification of differences and future actions for either party.

TADS/PNVS Program

When competitive contracts were awarded to Martin-Marietta and Northrop in March 1977, a strong DTC program, including tracking/reporting requirements and annual Army reviews, was included. Working from a three-year DTC base, the production contract RFP required both contractors to propose recurring hardware price objectives for all seven years of production, with commensurate rewards/penalties of up to $10 million per year based on the eventual negotiated prices. The special contract provision also contains mechanisms, proposed by the offeror, for treating changes in rate, quantity, projected escalation, germanium costs and the like.

Lessons Learned

During the course of recent U.S. Army DTC efforts, two significant lessons have been learned:

1. Design engineering rarely has available the tools necessary to conduct design/manufacturing cost trends. This is due in part to scarcity of detailed cost data on past programs, lack of validated cost correlating algorithms and an emphasis on cost as a function of manufacturing processes versus cost as a function of design approach. Cost data in the past have tended to become obsolete because of evolving technology, increasing automation, application of new materials, and variable inflation components on materials and labor.

2. Use of advanced materials and low cost fabrication techniques are extremely important for affordable systems design. This is contradictory to the extent that greater risk through lack of experience competes with the superior intrinsic qualities associated with materials such as high modulous organic composites, isostatically pressed castings, and super hard steels. Nonetheless, a prime consideration of DTC is to stimulate the designer to develop innovative design configurations which minimize both technical risk and manufacturing cost.

PRODUCTION

Producibility Design

The United States Army has found it both desirable and necessary to emphasize producibility as an adjunct to Design-to-Cost management. Both product engineering planning (PEP) and manufacturing methods and technology (MM&T) are vigorously employed. It was recognized early in the development of the T-700 engine that the compressor represented a significant cost driver. Very precise geometry combined with a labor intensive pantograph machining process dominated engine costs. Under an ambitious MM&T project, the production process was converted completely to numerical and computer controlled machines. Computer software was written and debugged, and prototype parts made. At the same time facilitization funding was provided by the Army to capitalize a dedicated compressor machining center at the General Electric plant in Hookset, New Hampshire. It is anticipated that after full amortization of the Government investment, a net savings of approximately $15,000 per engine will result.

In another MM&T effort the Army is financing Hughes Helicopters' efforts to manufacture the main rotor blade of the Advanced Attack Helicopter using automated filament winding techniques in lieu of a bonded metal construction (Figure 7). It is envisioned that this project will not only result in a much lower cost and more rapidly produced main rotor blade, but will also pay significant dividends in operating and support costs due to the ruggedness and field repairability of composite structures.

DTC drives a clear requirement to perform producibility planning and manufacturing technology efforts in parallel with the system design and qualification process. PEP and manufacturing engineering personnel must be in the sign-off process on design and be available to assist the designer when needed. This insures early acceptance of technology and results in nearer term return on investment.

Design for Reliability

Growing emphasis on ownership costs for complex equipment once it is fielded is being felt in nearly every stage of the development process. Design for accessibility, modular interchangeability, standardization of components, interoperability and a host of other techniques are being employed. Self diagnosis and built-in test equipment combined with automated inspection and repair at intermediate and depot levels are increasing. Simplified repair procedures, easy to read manuals and, in the near term, computer stored maintenance and diagnostics using fault tree logic to optimize trouble shooting for repair are being used.

Reliability Improvement Warranty

Definite reliability goals are customarily established for both systems and components. One technique which has been very beneficial to the Army is the Reliability Improvement Warranty. Under this process, in return for a negotiated fixed price at the beginning of the contract, the manufacturer agrees to repair all faulty parts and further to modify items produced so that a minimum contractual mean time between removal is achieved in the field. The light weight Doppler Navigation System (ASN-128) exemplifies the Reliability Improvement Warranty approach. If Doppler components fail in the field they are removed and returned to the manufacturer who also maintains a storage level in the supply system so that aircraft are not sidelined for lack of components. Incoming inspection at the contractor facility establishes whether the failure is charged to the contractor or to the Army (as in the case of maintenance induced failures). The contractor then repairs the component and returns it to the supply system.

Early in the Doppler program, infant mortality of lights, switches and several electrical components forced some redesign and additional quality control to meet the Army's MTBR requirement. This was done and the Doppler now is exceeding contract requirements on the UH-60 Black Hawk. The Reliability Improvement Warranty has been also applied to the T-700 engine, to the fiberglass rotor blade built by Kaman Aerospace Company for the modernized AH-1S Cobra helicopter, and is a part of the TADS/PNVS production contract. It is a very useful tool in establishing early confidence that field reliability will be, in fact, achieved without undue cost exposure by the Government.

In addition to the direct benefits of assured availability and reliability of a warranteed component, a number of indirect benefits have been realized. These include:

1. In order to price the warranty, both the contractor and the government must emphasize reliability and maintainability (RAM) features during the design process and attempt to accurately establish the RAM characteristics of the fielded equipment.

2. To exercise the warranty it is necessary to collect accurate and timely field reliability data. Field data is the bread and butter of the closed-loop reliability program. A data system has been developed called Component Report for Intensive Management (CRIM). This data system would be necessary even without warranties, but it receives additional emphasis and support from management because of the warranty program.

3. Unanticipated, early failures can have a very significant impact on the logistics support. The warranty program provides some insurance against these problems by providing for parts and labor for these failures. This is an obvious benefit to the logistics manager at the very busy time of the initial fielding of the system. In addition, the data that is collected under the CRIM system provides very timely information to assist in optimizing the spare support.

4. It is anticipated that the repair procedures will be impacted by the warranty program. The manuals that are generated for depot level repair have a tendency to be overstated primarily to protect the integrity of the design during the overhaul process. As experiences are gained on the product, the overhaul limits tend to reach an optimum level. This usually takes a process of years to accomplish, and in the case of the Government, it may take even longer. The process for optimization of the repair will be speeded up with the warranty program because when repairing warranted failures, the contractor is motivated to provide the corrective action at least cost that will insure product integrity. He will seek the optimum repair procedures by challenging his own engineers as to what the acceptable limits are for repair or scrap. This visibility will form the basis for the depot support activity over the life cycle of the product following the warranty period.

CONCLUSION

Before the advent of Design-to-Cost emphasis was placed on increasing performance with little consideration of affordability. After nearly eight years of experience, it is evident that DTC goals have discouraged demands for additional performance that would have increased production costs. In fact, DTC goals and constraints, which initially were based on preliminary cost performance relationships, may have become more important than technical requirements during design and development.

The expanding pressures of inflation, system sophistication, international agreements, scarcity of materials, and labor costs continue to sharply erode the ability of all military forces to procure necessary defense systems. DTC is an extremely important step in countering this erosion. DTC is thus a required and vital tool for the designer throughout the preliminary and detailed design phases of aircraft development. DTC targets must be established during concept formulation where cost flexibility exists to maximize total system performance for the funds available.

DTC has been a U.S. DOD acquisition policy for more than nine years. During this period many defense related periodicals have presented articles reporting great success with DTC concepts. Some of these reports may have been premature and overly optimistic in offering an evaluation of the total objectives established for DTC. While there is no question that acquisition managers are much more cognizant of system costs and production cost management since the introduction of DTC, one should not overlook that total DTC implementation required harnessing operating and support costs which constitute a greater portion of life cycle costs.

Design and implementation of Design-To-Unit-Production-Cost concepts have been substantially productive in achieving lower production costs through trade-off analysis and control of technological competition. In a sense, DTUPC has reduced the tip of the iceberg, but the base of the iceberg--operating and support costs--still requires application of resources and commitment from the user as well as the designer. There has been great achievement in the production cost spectrum, but limited success in the larger area of O&S costs. This is the next area where management attention is required if the real objective of reduced total ownership cost is to be achieved.

Figure 1 U.S. Army Design-to-Cost Summary

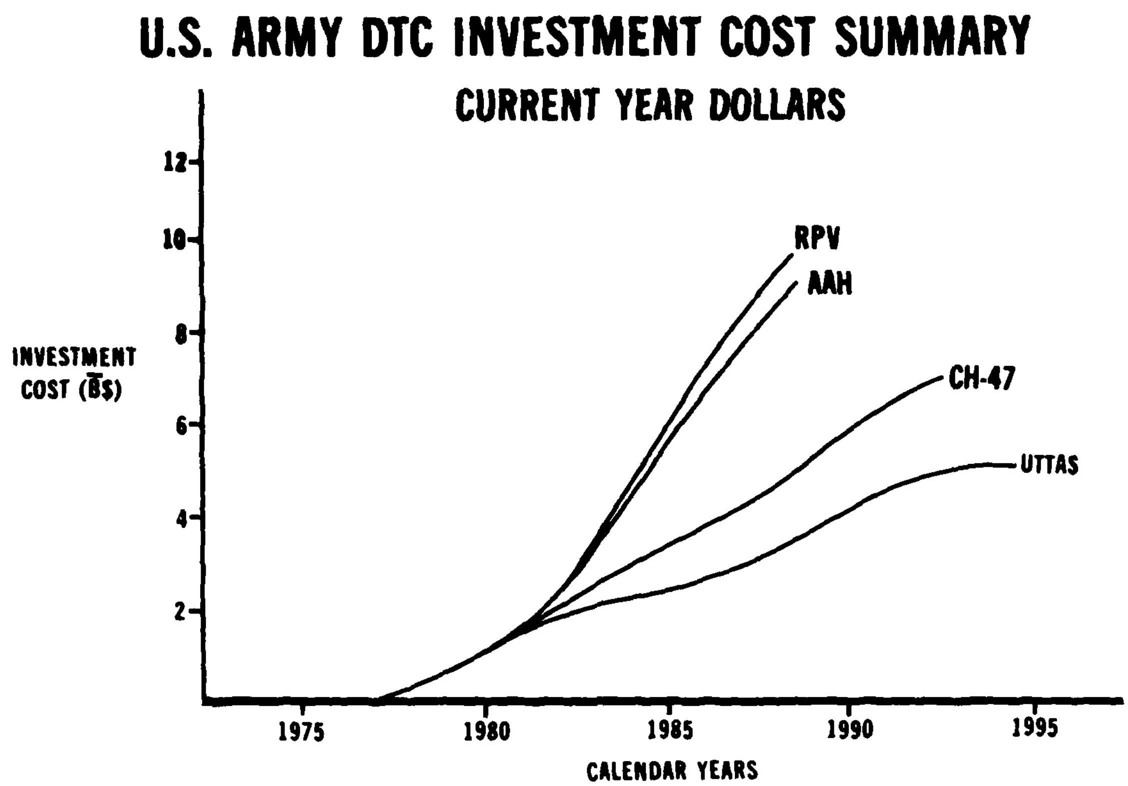


Figure 2 Life Cycle Cost Components

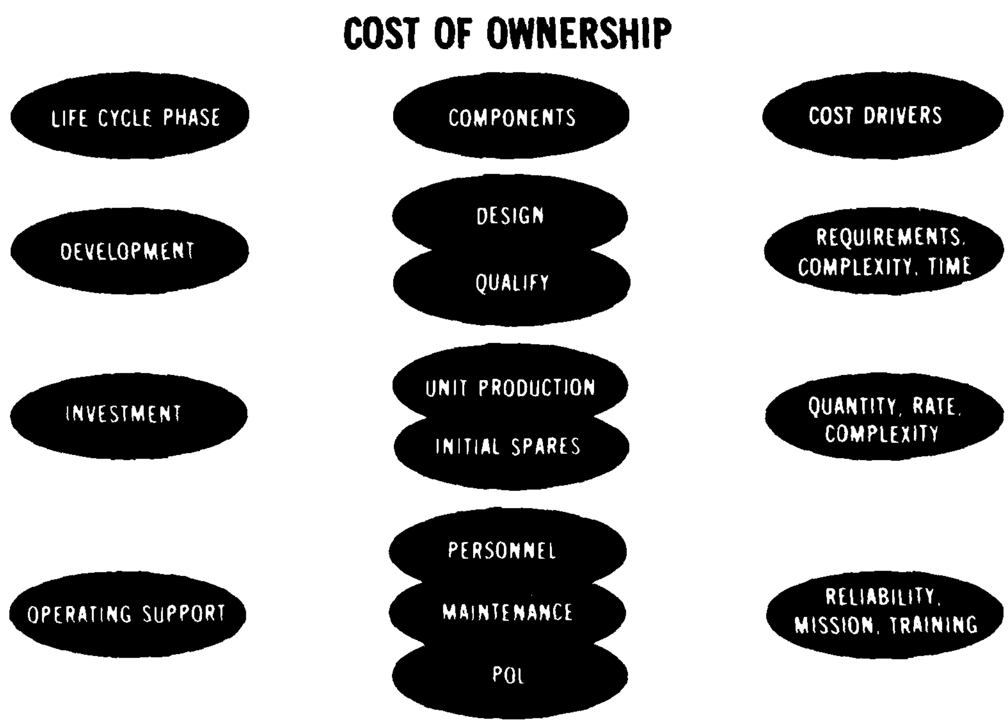
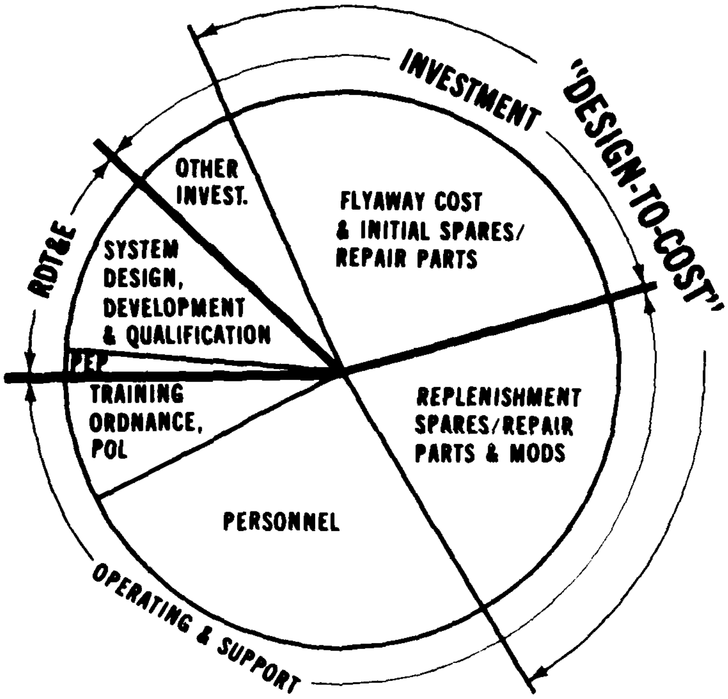
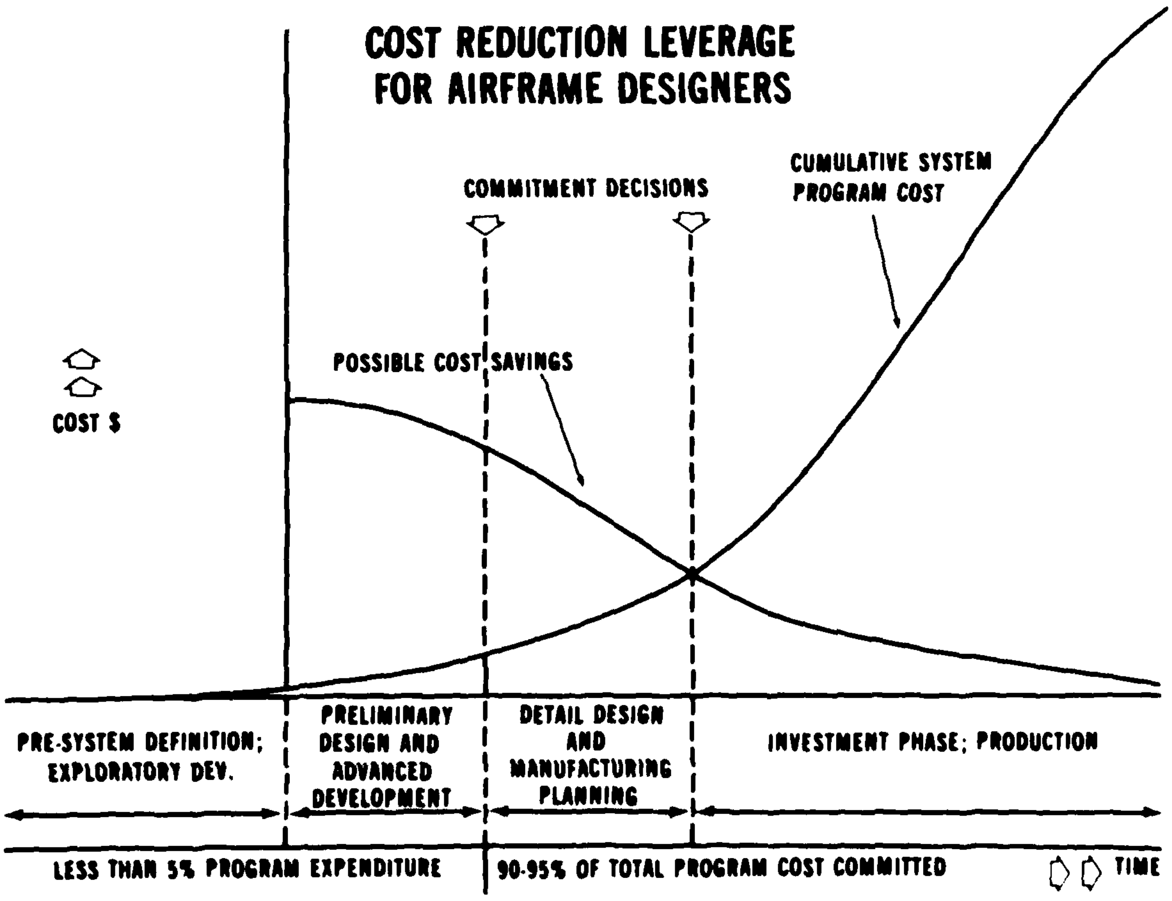
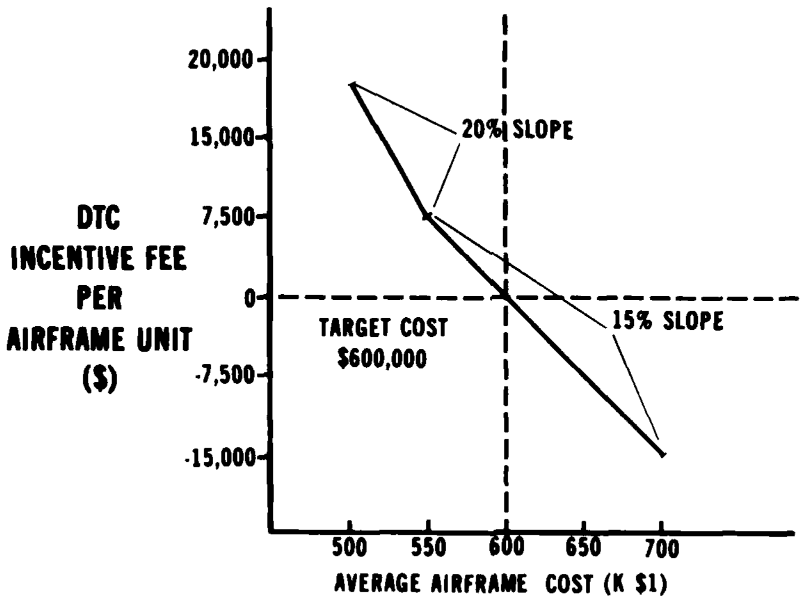


Figure 8 Life Cycle Cost Components

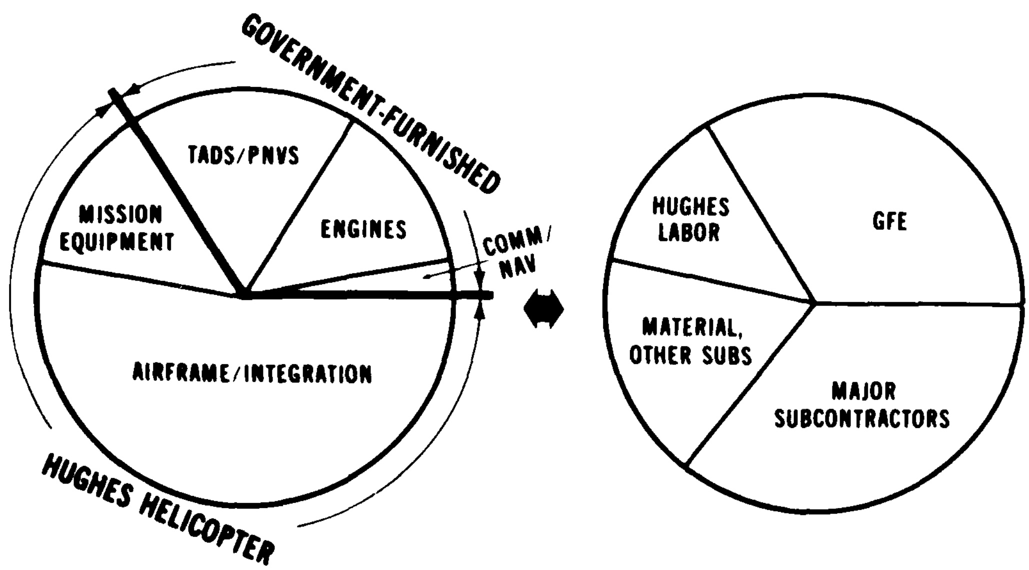




DTC FEE STRUCTURE FOR UTTAS CONTRACT

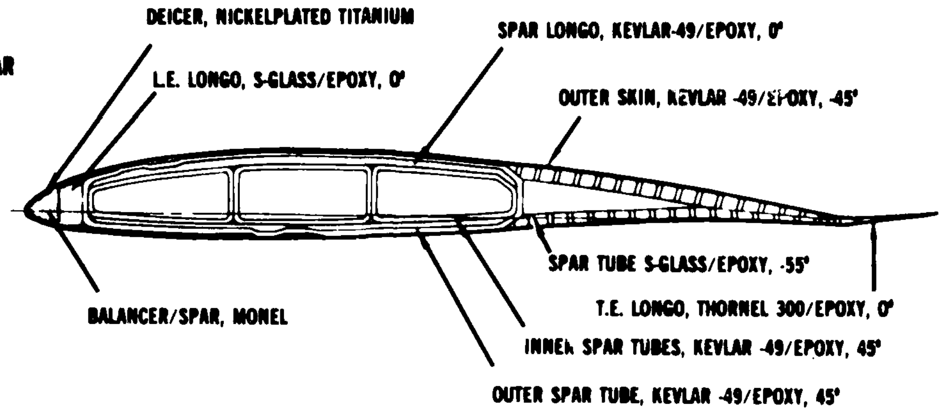


AAH DESIGN-TO-UNIT PRODUCTION COST



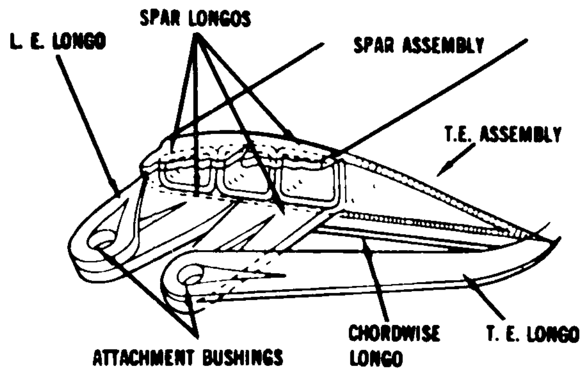
YAH-64 COMPOSITE MAIN ROTOR BLADE

- MULTI-TUBULAR SPAR
  - HUGHES MTS
  - KAMAN IMRB



- ROOT END WRAPAROUND
  - HUGHES MTS
  - BOELKOW BO-105
  - BOEING-VERTOL CH-47 (MOD)

- COCURE
  - HUGHES MTS
  - BOELKOW BO-105



A REVIEW AND ASSESSMENT OF SYSTEM COST REDUCTION ACTIVITIES

by

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ABSTRACT

The ever increasing cost of aircraft and missile weapon systems has led to growing concerns and the evolution of a number of concepts and activities to reduce cost. Nevertheless, the trend of ever increasing cost is still evident. This paper will review and assess the evolution of cost reduction concepts over the past decade to current Design to Life Cycle Cost (DTLCC) efforts. Emphasis will be given to progress achieved and basic problems and issues which have confronted successful application of these concepts. The review will address the importance of top management action, consideration of costs in the early phase, and a credible data base. It will discuss progress in developing cost prediction and analysis methods, technologies to reduce development, acquisition, operations and support costs, the institutionalization of design to cost and design to life cycle cost methods, and remaining challenges.

I. PURPOSE

The purpose of this paper is to review and assess the background and evolution of military aircraft systems cost reduction concepts over the past decade, summarize the substantial progress made, basic factors, problems, issues, and opportunities afforded by new technology, and highlight a number of challenges remaining for management and engineering solutions.

II. INTRODUCTION

The continual rise in military weapons systems acquisition and operational support costs, is certainly not news. It is a well known problem that has long aroused the concern of top DOD, Air Force and Industry management. Attainment of a credible program to reduce the total life cycle cost of both the individual and total complex of systems continues to be a major challenge for the military strategists, systems managers, designers, engineers, operators, logisticians, and all of the many other skills involved in the development of concepts and activities aimed at containing or reducing cost. These concepts and activities are still evolving and there is still much to be done.

It must be recognized, in any discussion of life cycle cost, that military weapons systems are designed to help prevent, and if necessary, win a war. In any campaign to reduce cost, or design to an 'affordable' life cycle cost, care must be exercised not to impair the military capability to the point where the balance tilts in favor of the enemy. If that happens the effort to save cost will result in an enormous waste of investments and perhaps much more. It must be recognized that the ever increasing cost of systems is paralleled by an ever increasing capability of the weapon systems so to some extent the actual cost/effectiveness may be rising less slowly than it appears when examining cost alone. It may even be decreasing in many areas. Life cycle costs are essentially peace time costs. Their rise is alarming, especially in peace time, but the improved military effectiveness could reduce the cost of performing a military mission during a war. Cost reduction is necessary, but it must recognize the importance of maintaining adequate military capabilities.

The causes of the ever increasing cost of weapons systems are many. They can be categorized in many ways, but it is clear that major reasons for high cost are associated with the acquisition strategies, economic and political factors, budgetary fluctuations, and contractual techniques, all to some extent beyond the control of the program manager and project engineers. Another major category of cost increases are due to the sophisticated technology and the ever increasing complexity of new systems in order to meet demands for improved military capabilities. Still another group are the cost problems in the operations and support phases of a system program, much of which is part of the institutionalization of the way these activities are carried out. The system design can exert a major impact in this area, but many of these factors are also beyond the control of the system developer.

Other ways of categorizing the problem could be described, however the above three represent major contributions to the life cycle cost of a system. Since they are inexorably intertwined, all three will be discussed to some extent, recognizing of course that a single paper such as this can only address limited aspects of what is indeed a cosmic problem, as termed several years ago by Dr. Sanator, Chairman of the National Security Industrial Advocation Ad Hoc Group studying the LCC problem for DOD.

Many concepts and efforts have been introduced in the effort to curtail or reduce the ever rising cost. Some have simply been an effort to increase awareness. Others have been aimed at very specific parts of the problem, for example to improve reliability. Much effort has been aimed at improving the acquisition process, but until recently relatively little effort has been aimed at improving the complete front-end portion of the process.

While it can be said that cost has always been an engineering parameter and has traditionally been given attention in system design, the facts are that this alone is not

enough, since costs have been rising. The increased awareness is beginning to provide greater emphasis on the cost aspects of the problem during the design process, but much more remains to be done.

III. THE PROBLEM

The cost of acquiring and operating aircraft and missile weapon systems is of major importance to the downstream effectiveness of the military force. As the slice of the national budget devoted to the military forces is generally reduced during times of peace, when other national needs are given priority, the ability of the military services to maintain an adequate state of readiness with effective modern equipment becomes increasingly dependent on the ability to reduce the continual trend of increasing development, production and test, i.e. (Acquisition) cost and operations and support, i.e.(ownership) costs, which comprise the total life cycle cost (LCC).

Cost is a continual major problem. Figure 1[1] shows the ever-increasing cost of procuring military aircraft and missiles. Projection of these figures has led to estimates that if the current trend of exponentially increasing costs continues over the next 40-60 years, the entire Air Force budget would be required to fund a single aircraft system. Calvin Coolidge, a U. S. President some years ago, is reputed to have said "Why not buy one aircraft and let the pilots take turns flying it". If something is not done to control costs, we might approach such a situation!

In addition to increasing acquisition costs, operations and support (O&S) or ownership costs are also rising as manpower, spare parts and fuel costs continue to escalate. O&S costs over 10 to 15 years frequently equal or exceed the total systems acquisition cost, as can be seen from Figure 2, a situation now well known to many as a result of the continued attention being given to the cost problem. Figure 3 from N. R. Augustine[2], shows typical times required for ownership and acquisition costs to become equal. The increasing ownership costs absorb a larger share of the Air Force budget and reduce the funds available to modify or procure new aircraft to upgrade force capabilities.

Much progress has been made in creating an awareness among government and industry management and engineers of the importance of cost reduction and in establishing procedures and processes that result in reduced cost. Cost reduction in the many areas, activities and factors involved, even though some may be small, can aggregate into significant savings. Significant progress has been made in designing systems for reduced production and support cost, in utilizing new technologies to reduce cost, and in evolving the systems acquisition and logistics management process, which exerts a major influence on systems cost. A number of the most significant gains to be made, however, are impeded by basic problems that have long existed and defied a solution. They continue to offer a management challenge that will handsomely reward success. Some of these are:

1. Lack of continuity in key management and decision making positions.
2. Inadequate emphasis on the front-end of the development process and trade-offs of the military requirements, system design and life cycle cost aspects.
3. The requirement to spend money now in order to hopefully save much money later.
4. Technical uncertainties.
5. Increased capability and complexity of most new weapons systems.
6. Budgets cuts and fluctuations.
7. Lack of credibility and the cosmic nature of life cycle costing.
8. Difficulty of credible trade-offs between future system operational effectiveness with peacetime life cycle costs.
9. Difficulty in establishing 'minimum - but acceptable military requirements for a new system and optimizing the force structure with total size constraints.
10. Demotivating influence due to contracting mechanisms. Excessive reviews, checks, audits, inspections, paperwork and regulatory requirements.

While many of the above factors are beyond the control of the Air Force/Contractor development and acquisition team, some will yield to continued efforts to find a solution. Further examination of some of these factors is warranted.

It was aptly stated by a top DOD manager, Mr. Schermer, some years ago that the basic problem is:

- A 10 plus year system problem
- A 5 year program
- 3 year people
- 1 year funding

The problem's still much the same. In fact some of the people are in place for less than three years! On the other hand, some program managers have remained on the job much longer.

The difficulty of convincing decision makers to spend money now to achieve a future benefit is always difficult, but is compounded by the questionable credibility of the anticipated future gains, the discount value of the future dollar saved in comparison

to the dollars that must be spent now, and the need for a current office holder to authorize spending the money when he will unlikely be in the same position when the benefit materializes. If a 10 percent discount rate is used, an expenditure of 39 cents now would require a savings of 1 dollar to obtain equal value 10 years later.

Technical uncertainties increase with system complexity and utilization of multiple new technologies. Technical uncertainties also increase when the system design does not provide adequate testing or margins to account for data scatter and other factors which experience has shown to be necessary. Design to the limits of the technology increases the probability of subsequent problems. The size of cost uncertainties can be substantial because of data base deficiencies and lack of accurate cost estimating methods, but when combined with technical uncertainties, the result can be a major program problem coupled with a major cost increase.

Figure 4 depicts conceptual cost/performance curves with bands of uncertainty for an existing system, a potential modification of the existing system, and a new system. Bands of uncertainty always exist, but are not often given adequate attention. The band of uncertainity is normally greater for the new system. Modifications to existing systems are one of the prime ways of improving operational capabiltiy within a relatively short time at small additional cost. Optimistically, a modification to System A to attain the capability shown by Point B would provide worthwhile improvements in performance for the incremental cost shown. With advanced technology, it may appear possible to develop a new system with much greater performance, for the affordable cost (Point C). Unfortunately failure to take into account uncertainties in either the modified or new system often leads to cost overruns, such as that shown by B1 and C1. Performance degradation could also result and cost C1 could rise within the uncertainty band to C2 The capability for probabilistic analysis and design might help avoid the problem, but that's tough to do. As a minimum, the degree of uncertainties should be analyzed so that judgments regarding probable performance and cost can be based on reasonable knowledge of the probabilities.

Budgetary fluctuations during the course of major programs frequently force reprogramming and re-scheduling the work effort, and result in major inefficiencies in productivity. Stretch-outs, and delays caused by the reprogramming process result in losing knowledgable people to other jobs, retraining costs and require many people on the payroll for a longer period of time, thereby increasing total cost. Further these fluctuations cause a costly reverberating effect throughout the entire industry that impacts thousands of vendors, suppliers, and subcontractors, as well as the prime contractor.

The inadequacies of the life cycle cost data base, and the sheer complexity and magnitude of the problem lead to low confidence in life cycle cost estimates. Failure to provide front-end funding to implement the actions required to attain future O&S savings lead to a lack of credibility of the concept in the eyes of those who have to do the job.

Weapon system life cycle cost reduction involves a 'cosmic' myriad of interacting factors encompassing all aspects of system development, production, test, and support. It involves the development and application of new technology, nearly all scientific, engineering and logistics disciplines; military planning, requirements, and strategies; systems development and logistics management; systems acquisition strategies, personnel training and productivity; and an enormous array of military, design, and process methods and specifications. Many of the specifics involved in the above areas are relatively micro in nature but aggregate to become major cost factors. Several broad aspects, such as military requirements, preliminary system design, systems acquisition strategies, and O&S concepts exert major influences on the system life cycle cost.

One of the continual concerns associated with major acquisition cost reduction programs is their possible impact in reducing weapons systems operational capability. Field commanders are, of course, interested in having quality weapons systems in adequate quantity. The emphasis in reducing cost often results in emphasis on meeting the "minimum military requirements" estimated as being necessary to accomplish the expected military missions. Many uncertainities exist in estimating the minimum needed capabilities, and a military commander naturally would prefer the most effective possible weapons system within his authorized number to do the job. Much has been said about the possibility of lower cost systems permitting an increase in the numbers available to operational commands. Unfortunately, this is not necessarily so, since many other factors dictate the number of authorized operational aircraft and wings. The substitution of a less expensive and less capable weapons system in order to reduce cost cannot be expected to receive the enthusiastic support of field personnel unless it will with some certainty be compensated by adequate increases in quantity or other important factors. One advantage offered by the reduction of life cycle cost for a new system, is that it can relieve budget pressures and possibly result in more frequent modernization of the authorized number of wings and aircraft.

Field commanders are also highly concerned about achieving high availability of their systems for operational missions. To the extent that reduced O&S costs are achieved through increased reliability, maintainability, servicability, and other factors important to attaining effective operational capabilities, the effort to reduce O&S costs offers the possibility of accomplishing both important objectives.

Life cycle costs relate to the design, development, testing, production, operations, support, and where applicable, the disposal cost involved over the entire life of the weapon systems. The operations and support costs relate to the peacetime cost of maintaining the prescribed state of readiness. Reduction of total life cycle costs represents a major need, but if a major war comes, the operational performance, readiness, and sustainability of combat systems will be by far the most critical need. Continual actions to provide both short and long term solutions to the life cycle cost problem must never forget the importance of this.

IV COST REDUCTION CONCEPTS & SYSTEMS ACQUISITION

Over the years, many methodologies and concepts have been introduced in an effort to achieve meaningful cost reductions. These have been accompanied by much rhetoric, and in many cases, extensive campaigns to improve awareness of the need to consider cost in all aspects of system development and use. Figure No. 5 summarizies a number of past and recent cost reduction slogans and methodologies. During the past decade, many policies and directives have emerged, and 'design to cost', with consideration of 'full life cycle cost' is now being institutionalized in order to make it a normal way of doing business.

Early Cost Reduction Considerations - During the 1950's, each service developed it's own system acquisition strategy within the budgets that were allocated yearly by DOD on a percentage basis to each service. Programs initiated during this time period often provided the ground work for an increased share of the budget during future years. A number of programs entered the relatively low cost initial stages of development, but could not be supported by the available budgets as the system entered the more costly development and production phases during the subsequent years.

The prime "cost" reduction technique during this period and early 60's appeared to be a 'meat axe' approach, i. e. cancel the program, or in some cases, stretch-out the program to reduce the yearly cost. This led to many program cancellations and funding problems as programs were stretched-out in the hope for next year funding. One can make the case that competition is good, and having a large number of programs options is an ideal situation. The problem was that many options were continued and stretched until overcome by events, with hundreds of million dollars lost, except for the knowledge gained in the process.

Prime emphasis in aircraft design during the late 40's and early 50's was on the airframe, propulsion and payload in order to achieve significant improvements in performance made possible by the turbojet engine and thin or swept wing technology. Manufacturing techniques to achieve the high production rates demanded by needs during wartime obviously received major attention, but cost was not the major consideration. The continual demands for improved performance greatly increased systems complexity and led to many systems integration and reliability problems. This growing need to consider the entire system, led to introduction of the full aircraft weapons system concept with the B-58 in the early '50's, and increased attention on more effective systems and subsystem integration, especially in the areas of avionics.

While cost of a new systems acquisition was obviously a factor given much attention, the prime emphasis continued to be on improvements in the engineering and system development process to avoid or eliminate costly problems and improve overall programs development efficiency and effectiveness. Concurrency was a prime mode of operation in order to reduce time to operational deployment, but except for a few, such as the ICBM program, budget fluctuations and technical problems thwarted the reduced acquisition time objective.

During the 1960 time period, DOD initiated the five year Program, Planning and Budget System (PPBS) together with DOD control over major system acquisitions. The development concept paper (DCP), now known as the Decision Coordinating Paper, was established as the basis for 'decisions' at the key milestones established for initiation of each of the program phases which were defined for the system's life cycle, namely the conceptual definition, acquisition, and operational phases. Major considerations and activities necessary during the first two phases are shown below:

Concept Formulation Phase:

- o Engineering and analytical studies
- o Technical, and economic, and military basis for a DOD 'conditional approval for development'
  - . Definitions of Missions and Performance
  - . Selection of best technical approach
  - . Analysis of trade-offs for cost, schedule and performance.

Program Definition Phase:

- o Establishment of firm and realistic system and equipment specifications
- o Definition of interfaces and responsibilities
- o Identification of high risk areas
- o Explorations of trade-offs and alternatives
- o Selection of best technical approaches
- o Establishment of firm and realistic schedules and cost estimates
- o Formulation of realistic logistics support and operational concepts
- o Establish the ground-work for a fixed price or incentive contracting for the major part of the program.

Note that there is emphasis on cost estimates and trade-offs and on the establishment of logistic support and operational concepts which exert profound influence on life cycle costs, even though the concept of design to cost or design to life cycle cost had not yet clearly emerged.

In addition, the 'Total Package Procurement Concept' (TPPC) was developed for concurrent negotiation and procurement of the complete development, production and logistic support systems acquisition, with use of the competition during the concept formulation phase as a leverage for these negotiations and fixed price contracts. This technique, which was used for the C-5A, required the contractor to commit to the total cost and performance of the system before the design was complete. Further, a policy of Government 'disengagement' reduced correction of problems during the development. The result was a billion dollar plus problem and a series of claims and adjusted payments.

Systems management came to be recognized as a factor of major importance in a system acquisition, and in mid 1964, the Air Force Systems Command 375 Series Manuals were issued to establish a more standard and effective approach to systems management. In the foreword, the Commander of the Systems Command, General Schriever said "Many times we have found the pacing factor in acquiring new weapons, support and command and control systems is not technology - it is management. All too often technology has been known, but it was not properly put to use because of shortcomings in our management ability....The leading endeavor in this advancement is in system management ....I consider it essential that every person performing system program functions, read, understand, and comply with the philosophy described in the manual."

Program documentation was defined in much detail to meet the requirements of the DOD 'Program Package Concept' and the many system management procedures. Unfortunately, compliance with the extensive array of specifics, rather than the philosophy and guideline aspects of the manuals was gradually interpreted as a definite requirement, and the System Program Offices (SPO's) were forced to develop and process an increasingly large amount of costly paperwork.

The 1970 Decade: A revival of prototypes and a new era of systems management philosophy began shortly after the change in DOD administration in 1969. Deputy Secretary of Defense, David Packard took a strong interest in the systems acquisition process and the problems posed by the ever increasing costs. In an article several years later, he said, "As I reviewed program after program beginning in the spring of 1969, almost all were in trouble from a common fault - production had been started before engineering development was finished." In 1970, he mandated that all defense systems be developed on a sequential schedule, with no movement to the next phase of development until all problems discovered during the previous phase were fully resolved. He noted that 'the ideal schedule is sequential with enough slack time for resolution of those problems which invariably arise in any development program.'

He took other firm actions to eliminate many problems which impaired effective systems acquisition management, and by May 1970, had established a set of policies to:

- . Cut out numerous layers of authority
- . Reduce directives and regulations to a minimum
- . Encourage initiative and innovation
- . Manage programs with more capable people
- . Give Program Managers responsibility and authority
- . Assure continuity to get the job done right

A new series of DOD Directives, starting with 5000.1 in July '71, followed to institutionalize his policies for systems acquisition. DOD instruction 5000.1 established a new 'full-scale development' step in the acquisition process and provided emphasis to the establishment of:

1. Cost parameters which consider the cost of acquisition and ownership.
2. Discrete cost elements (e.g., unit production cost, operating and support costs) translated into 'design to' requirements.
3. Continuous evolution of system development against the 'design to' cost requirements with the same rigor as that applied to the technical requirements.
4. Practical trade-offs between system capability.

The philosopy of 5000.1 continued to evolve as further DOD Directives more specifically defined the development steps, and established a series of Defense System Acquisition Review Council (DSARC) reviews at the key milestonesof the acquisition process. Following a review of the process by the Congressional Commission on Goverment Procurement, the U. S. Office of Management and Budget (OMB) issued Circular A-109 on 5 April 1976. This establishes the current policy in the U. S. for major system acquisitions. Its prime objectives are to 'greatly reduce cost overruns and to diminish the controversy of the past two decades on whether new systems are needed'. This document stems from the philosophy expounded by Mr. Packard and the development of the DSARC review system. It clearly recognizes the importance of the 'front-end' of the acquisition process, and places much emphasis on clearly establishing mission needs, developing alternative competitive solutions to the validated needs, and avoiding premature commitments to full scale development and production. A-109 requires a continuing analysis of current and forecasted mission capabilities, technological opportunities, overall priorities and resources that are involved. Deficiences in mission capabilities must be documented in a mission element need statement (MENS) which requires formal approval by the Secretary of Defense, (Milestone 0), before proceeding into the first phase of the systems acquisition. It is highly logical and elegant in concept. Figure 6 compares the steps in the acquisition process as evolved from 5000.1 with the earlier process and shows the DSARC reviews and new milestones of A-109.

Design to Cost: DOD Directive 5000.1, "Acquisition of Major Defense Systems" on July, 1971 constituted the first official DOD policy statement on design to cost (DTC) and life cycle cost (LCC). These were made much more specific with DOD Directive 5000.28 "Design to Cost in May 1975. Scope of the design to cost and life cycle cost definitions relative to the major phases of a system's life are shown by Figure 7.

"Design to Cost" is defined as a management concept wherein rigorous cost goals are established, and control of life cycle costs to these goals is achieved by practical trade-offs between operational capability, performance, cost and schedule. Cost is considered a key design parameter to be addressed on a continuing basis. One of the key objectives of "design to cost" is to establish costs as a parameter equal in importance with the technical requirements and schedules throughout the system life. Since the ability to accurately estimate production cost is far better than that to estimate operations and support (O&S) cost, the initial "design to cost" goals were established in the form of average unit fly-away costs. The management objective, supported by various plans and reviews, also includes the control of future O&S costs, although specific design to cost goals in this area are dependent upon the development of an adequate cost data base.

The A-X prototype program, which led to the A-10A, was the first major system to adapt the DTC concept. The A-X competitors were given a specific unit production cost goal for their aircraft, and total program cost (operation and support, as well as acquisition) was established as an important source selection evaluation criteria. During design of the YA-10, engineers were given cost 'bogies' as well as weight 'bogies' which are traditionally given as design goals. Efforts were made to provide for common left-hand and right-hand parts, single curvature shapes, use of conventional materials to reduce manufacturing costs and improve maintenance accessibility to enhance maintainability, and lower support costs.

Life Cycle Cost: Continual concern about the rising O&S costs led to the evolution of a number of techniques to assure consideration and assessment of full life cycle cost considerations. These included policy statements, such as that of the Commander of the Air Force Systems Command, in March, 1975 summarized in Figure 8 . DOD policy evolved to require the program manager to submit plans for achievement of O&S cost goals, review by top systems management and the Defense Systems Acquisition Review Council (DSARC) of trade-offs to establish the best balance between acquisition and O&S cost and minimize total life cycle cost. Some teeth were provided by introduction of specific quantitative requirements, such as Meantime Between Failure (MTBF), Maintenance Man Hours per Flight Hour (MMH/FH), new procurement incentives, and Reliability Improvement Warranties (RIW's) to reduce O&S costs.

The RIW objective is to motivate and increase contractual incentives to produce equipment which will have low failure rates and repair costs. RIW is included in a fixed price acquisition or equipment overhaul contract to motivate the contractor to improve the equipment engineering and production design so as to achieve improved operational reliability and maintainability of the system component. The warranty requires the contractor to replace or repair all failed equipments within a specified time during the covered time period. Ideally the price for the RIW covered is negotiated as part of the acquisition contract during the competitive period. Inclusion of such features, of course, requires additional funding at the time of program acquisition. Their use adds credibility to the DOD intent to seriously consider life cycle cost, and provides increased front-end funding

Emphasis was also given to improving the DOD/Industry and interface in both the design to unit cost and the design to reduce O&S cost areas. Contractors have been provided increased visibility into the O&S cost structure, and have become highly involved in the analysis of O&S cost and techniques for their reduction. The importance of the early design process has been more fully recognized, and major efforts have been made to provide designers with an understanding of life cycle cost parameters so that the implications of such cost can be more fully considered and traded off during the design process. Inadequacy of the data base, especially in relation to its ability to quantify the impact of specific system characteristics and deficiencies on O&S cost has inhibited more exten

sive integration of specific O&S cost design requirements, but efforts are underway to remedy the situation.

Commercial practices are being analyzed to both determine their applicability to the military problems and to provide the cost benefits achieved by the effective commercial experience in airline and airfreight operations. As an example, the T-37 total training system now in procurement includes consideration of commercial practices in the request for proposal. The KC-10 tanker program involves contractor support, commercial warranties and other commercial practices. Buy plans for a new cargo aircraft includes considerations for contractors support during the first three years of operation, and various incentives for interim contract support (ICS) with a fixed price for follow-on support. One concept includes an adjustment of the incentives and cost sharing aspects to not only motivate the contractor to effectively accomplish the task, but to gradually phase out of the support activity as Air Force resources become capable of absorbing the load.

Definite progress has been made in the implementation of life cycle cost objectives, even though the capability of actual design to life cycle cost is still somewhat illusive. During the past several years, source selection criteria has involved consideration of logistics costs as well as acquisition costs. The life cycle cost plan prepared by SPO directors to establish goals provides visibility throughout the program for management of life cycle cost factors during the full scale engineering development, and production phases of the program. Costs are identified for the support, training, and spares by the System Program Office (SPO) which includes representation from both the Air Force Systems and Logistics Commands.

Life cycle cost reduction goals are set by establishing factors such as affordability limits, through comparison with similar systems, and by maintaining competition until negotiation is completed, for not only the systems acquisition, but for warranties and other guarantees for adequate performance during the operational phase. Mission oriented work statements are utilized to reduce the number of changes required by the Air Force. These replace the older type work statements which specified the product characteristics in detail and frequently required changes to assure that the product met intended military requirements.

The Air Force Light Weight Fighter Program which resulted in two prototype aircraft, YF-16 and the YF-17 utilized design to cost for both the prototype and later F-16A full scale development (FSD) and production costs. Unit target prices were established in the Jan 1975 for Fiscal Year 77, 78, and 79 production aircraft. LCC and RIW provisions were also included in the contracts. In the FSD bids, each contractor provided a firm fixed price option for RIW's and RIW with a MTBF guaranty for a group of 'First Line Units' (FLUs). A FLU is the first level of disassembly below the system-level that would be carried as a line item at the base-level supply. It is synonymous with an avionics component Line Replaceable Unit (LRU). Each of the FLUs was used as the basis for a support cost control program whereby the predicted logistics support cost established by the contractor was subject to a 3500 flying hour demonstration. Selected FLUs were expected to contribute 50% or more of the component level logistic support cost. An award fee was provided as an incentive for contractor achievement in meeting the 'Target Logistics Support Cost'(TLSC).

Affordability: Cost concepts continue to evolve. The concept of affordability, i.e. the ability to bear cost of something can be quantified by comparing the cost of a new system in relation to available budgets, and then adjusting the cost to be compatible with the budget, i.e. the affordable cost. The affordability concept was included as a factor in trade-off decisions by DOD Directive 5000.1 in 1971. In 1977, DOD Directive 5000.2 'Major System Acquisition Process' specified 'Affordability Objectives' and required that acquisition and ownership cost be shown as separate cost elements prior to full scale developments. The most recent draft of DOD Directive 5000.1 provides that affordability be determined at each DSARC review, and include the percentage of the defense budget in the system mission area which the projected system will require.

V. SYSTEMS ACQUISITION STRATEGIES

The systems acquisition process exerts a major influence on the development and production cost, and significantly impacts the effectiveness of the system and its follow-on operations and support cost. The process itself is one of the major cost drivers, strongly impacts the engineering design effort, and warrants serious consideration in any effort to reduce life cycle cost, or in a discussion of the subject.

Figure No. 9 provides an over-view of system acquisitions by the USAF, plus several commercial programs, over five decades. This chart shows the interelationship between basic acquisition goals or philosophies, the needs of the time era in relation to either peace or war, the type of system acquisition process, and the program start date for a number of aircraft systems. The top portion of the chart depicts the basic goals/philosophies. The center of the chart describes the emphasis given to various types of system acquisition processes. Aircraft programs started during each of the five decades are shown in the bottom half of the chart. It can be seen that a number of these programs are prototypes but that a number of others represent the initial production aircraft under a concurrency approach. The process used varies, despite the dominant philosophy of the time period.

An important point indicated by this chart is that the emphasis between a prototype 'fly before buy' and a 'concurrency' philosophy has varied back and forth over the years,

although of course never in the exact same manner. As noted later, the 'fly before buy', or prototype approach offers the opportunity to obtain flight experience on critical portions of the system before a commitment to full scale development or production. The objective is to solve all of the basic problems, reduce uncertainties, and sharpen ability to predict future performance times and costs for the subsequent production phase. Despite the advantages, the extensive stretch-out of programs resulting from such a step approach, with gaps between the major program phases, has often led to much concern about producing aircraft that are technically obsolescent. This, and needs dictated by war-time urgencies have led to various concepts to reduce the gaps between the major program phases, or to even overlap or merge these phases into a concurrency concept. Then, after experiencing the extensive and expensive problems and initial system inadequacies introduced by premature production, the prototype approach regains favor.

Each of the two major approaches, the prototype and the concurrency approach, has many advantages and disadvantages, and various efforts have been made over the years to modify each of these basic concepts to maximize its advantages. Much consideration has also been given to commercial aircraft development experiences, and it is to be noted that most new commercial aircraft are now developed without a prototype step. The need of a prototype clearly depends upon the magnitude of the differences between the new aircraft and its predecessors for which the manufacturer has experience and the basic state of knowledge and development capabilities. Choice of a tailored approach, which may involve a prototype, is more likely to provide optimum results.

The importance to both systems effectiveness and costs of the approach to systems acquisition warrants a closer examination of both the prototype and concurrency philosophies and the current acquisition process.

Prototypes: These and technology demonstration flight vehnicles offer many advantages in solving problems and reducing uncertainties, but also have a number of disadvantages. The pros and cons need to be carefully weighed in deciding whether the need for a prototype for a specific system under consideration warrants its cost. Without question, if included in the program a prototype will cost money and time. The question is whether or not it is likely to save more money and time than it costs, by eliminating costly downstream changes in production, as noted by Fig. 10.

Prototypes are generally advantageous when the new aircraft represents a major change from previous experiences or incorporates substantial new technology. Prototypes before production offer significant pay-offs in reducing uncertainties and resolving problems in systems integration and some aspects of cost. Another major advantage is the value gained by 'exercising' the design, manufacturing and test team, and in validating the engineering methods used in the design, development and test. This hones the design and development capabilities for the production aircraft and future developments. Other major advantages include the likelihood of using more advanced technology than would be possible with the lower risk program demanded for an initial production aircraft. The use of full fly-by-wire flight controls in the YF-16 provided an important bridge between laboratory technology and the follow-on system acquisition program. Had the program not included a prototype, it is highly unlikely that this technology would have found its way so soon into production and operational use. Prototypes also offer a significant advantage in permitting competition through a flight program. Examples of recent competitive programs are the YA-9 vs YA-10, YF-16 vs YF-17 and the AMST YC-14 vs YC-15. Of these, the A-10A, F-16A & the Navy F-18, which was derived from the YF-17A, have entered production. In contrast, the the high cost of FSD and production generally precludes competition. Prototypes provide relatively quick and low cost development and flight experience. The confidence gained is often critical to a decision to proceed into FSD or production.

Disadvantages also exist, and it is important to understand the real need for the prototype and assure that the objectives properly reflect these needs. The limitations of the prototype approach, which may introduce many short-cut methods not applicable to a production program and not include all aspects of the complete system, need to be fully understood and given adequate visibility in order to preclude a false sense of security following a successful prototype effort.

The flight prototype has often been viewed as necessary to validate the basic flight vehicle, but not the entire system. In the past, the flight vehicle was often considered to be the critical element in the system, since it represented an integration of many of the basic technical disciplines involved in flight systems, such as aerodynamics, structures, propulsion, flight control, the cockpit, pilot and the avionics required for flight. Postponement of adequate consideration to military mission avionics and armament in early prototypes often delayed achievement of a military capability because of inadequacies and delays in completing development and integrating these essential elements of a military system.

One of the major disadvantages of the prototype approach is the gap that results in the program engineering and manufacturing activities during the time the prototype is being tested, and later, while awaiting a decision on whether or not to proceed into full scale development or production. The extension of total time from initiation of the system to deployment because of such gaps is a subject of increasingly great concern, and properly so. This will be discussed in more detail in the next section. Another po[illegible]le disadvantage of the prototype approach, especially from the view of some top management, is the pressure to push every successful prototype development into production

INCREMENTAL APPROACH: The growing systems sophistication, and the inadequacies of flight vehicle prototypes which led to the introduction of the 'Systems Concept' during the early 1950's was noted on Page 4. This total approach to systems development, while not negating the use of a flight prototype, generally required the rapid availability of additional flight vehicles in order to permit completion of the aircraft performance, structures, propulsion, flight control, avionics and armament system tests within a reasonable time period. Since the production of 3 - 13 prototypes required production quality tools, although limited in scope, the initial batch of aircraft using these concepts are more aptly termed initial or low rate production aircraft. The problem with this approach with gaps between the steps, is shown by the Figures 11,12 & 13 on the 'Acquisition Cycle'. The program gaps associated with an incremental approach involving two prototypes, followed by a flight test program and assessment, and a limited quantity of 'Full Scale Development' aircraft for test and evaluation prior to initiation of production for inventory aircraft clearly extends the time to achieve an operational capability. Further, the major fluctuations in manpower loadings to accomplish the separated phases results in loss of highly knowledgable people to other activities during the gaps in the process, with resulting inefficiencies. Figure 14 compares military and commercial rate build-ups.

The incremental approach does offer some appeal. It tends to bound the Government risk, provides time to learn and evaluate prior to the next step, and allows for incorporation of changes, discovered necessary by tests, in the next phase of the program. It avoids some wasted effort in premature planning, tooling, and in establishing production lines for the next phase. If the step approach eliminates all of the basic problems before proceeding into production, excessive retrofit costs can be eliminated. The experience obtained during these steps also provides data and improves the ability to predict cost, schedules and performance of the next step. Further, the whole concept provides a more conservative approach in obtaining Congressional approval and avoiding the criticism engendered by a more risky approach. However, all of the hoped-for benefits from this process may not occur, because the evolving threat is more apt to require changes in the system as a result of the stretched out program steps. The cost of the gaps in the development process in terms of manpower loadings and loss of skill retention can more than compensate for the advantages gained by the step learning process. The cost of the gaps may exceed the cost of producing low production rate new aircraft in a continuous program.

Concurrency: The concept of concurrency, which means that long lead time production procurements and other activities are initiated prior to completion of the prototype or full scale engineering development is one that has periodically been the preferred acquisition strategy. Even when out of favor during the 1970 decade, it was still utilized for some system acquisitions such as the Trident program. Concurrency offers many advantages, but also has a major disadvantage which at various times has led to it being much disfavored. These are shown below:

Advantages:

- o Provides a powerful focus for all aspects of the program.
- o Permits a smooth transition from development to production.
- o Pushes earlier design maturity, and minimizes the acquisition time span to deployment, as shown by Fig 15 for commercial programs, most of which utilized concurrency.
- o Drives the total system (hardware, training, logistics, supports, etc.) to early operational deployment.
- o Reduces costs, when properly done.
- o Provides a workable solution for the 2 year plus lead time for critical materials, machine tools and forgings.
- o Provides early visability of production rate problems.

Disadvantages:

- o Starts of production before completion of engineering development greatly increases risk from unforeseen technical problems, requiring correction during production or operational service at great expense.

As a result of technical problems, cases exist wherein the concurrency approach, without inclusion of a prototype, actually resulted in a large number of production 'prototypes' rather than operational aircraft.

Technology Demonstrators and Systems Acquisition Strategy - A possible solution to the prototype issue is the use of technology demonstrators to provide the integration and demonstration required to mature high payoff new technology for application to a system. These can be less costly and quicker to accomplish than the prototype for a new system. They could be initiated as needed to resolve the technical uncertainities and provide a credible assessment of the technology payoff independent of the many issues facing initiation of a new system, thus providing valuable lead time. With the technology, and some of the important cost issues resolved by the demonstrator, the system development could be started with more confidence on a concurrency or 'tailored' acquisition approach. The cost savings accrued thru elimination of gaps in the system program could pay for the technology demonstrator cost by many factors.

A basic issue confronting initiation of subsystem and flight vehicle technology demonstrators, usually conducted under the Air Force's advanced development program, is determining whether the need and potential payoff for the new technology justifies the cost involved in a highly competitive limited fund area. Although less costly than a system prototype, the cost is not trivial, and may often run some 30 to 100 million dollars. As can be expected, expenditures of this magnitude receive very careful consideration throughout the funding system, and are not easily approved unless there is a clear well established need.

'Proof' of a clear need is aggravated by the some 3 to 6 year lead time required for the technology demonstration to be complete in time for use by the system. The need is seldom clear that far ahead. Yet, the decision to apply the technology to a new system or go with a more concurrent systems development in lieu of a prototype with costly gaps in the system program may well hinge on the knowledge and confidence gained by a technology demonstrator.

Application of 'fly-by-wire flight controls in the YF-16, the ride control (load relief, mode stabilization vanes) in the B-1, and the current series of advanced engines now in use are recent examples of technology demonstrators paving the way for application of advanced technology. In these cases, serendipity helped and the demonstrations were completed just in time for systems application.

The enormous cost of gaps and delays in a system program which could be avoided by the right type of technology demonstrators strongly suggest that a planned strategy of 'targeting', and supporting high payoff technology programs to be sufficiently completed prior to the definition phase decisions for a new system would pay major dividends in both cost reductions and systems capabilities. It should not be expected that all successfully demonstrated technologies and the anticipated system will come together at the targeted time. The planned system may not 'materialize', or the technology may not offer the hoped for payoffs, but the value of the 'hits' will more than make up for the strike-outs. Further, the addition to the technology base will likely be of value to other programs.

Current Acquisition Steps : As a result of A-109, key 'milestone' reviews have been established as a basis for the acquisition steps shown below:

- Milestone 0- Program initiation, concept development, and evaluation of alternative systems.
- Milestone I- Demonstrations and validation of one or more alternative systems.
- Milestone II- Full scale engineering development/limited production
- Milestone III- Rate production and deployment

Each of the milestones involves an intensive DSARC review before proceeding with the next phase of the program. The Milestone I review will also determine whether or not a prototype aircraft or a demonstration engine or set of avionics should be accomplished before proceeding into full scale development (FSD). The evolving process is incorporated in the most recent issue of DOD Directive 5000.1.

Figure 6 showed the current five phases of a major system acquisition program in relation to the new Defense System Acquisition Review Council (DSARC) reviews and A-109 milestones. A basic challenge will be to assure that this process, which can result in delays in starting a new prototype or full scale development is not implemented so as to needlessly extend the total time required to achieve an operational capability after identification of the threat and need. The continual changing environment, and new assessments of the threat, needs, and affordable costs as the program proceeds can be devastating to an overly stretched acquisition program.

VI. PRELIMINARY DESIGN/MISSION ANALYSIS

The preliminary design process, in conjunction with mission analyses represents one of the most powerful tools available for reducing LCC and providing key answers for systems development. The design process, shown on Figure 16, is a key phase of the systems acquisition process, both in exploring alternatives in the conceptual phase and in defining the system after initial go-ahead.

The process provides a highly effective technique for the continual assessment of new threats and mission needs, conceptual new systems, parameter sensitivities and interactions, impact of uncertainties, technical needs and the input of new technologies, both prior to the validation of the MENS for a new system and in the conceptual phase of the system acquisition program. For either use, it provides a superb learning opportunity for understanding the many interrelations involved between the threat, operational needs, systems, technologies, production, operation support and cost factors. It facilitates and provides a basis for meaningful communications between the engineers, managers, and specialists in the laboratories, system development organizations, cost analysts, logisticians and operational personnel.

Terminology varies, and I am using the term 'preliminary design' in the broad sense to include the entire conceptual and preliminary design and development process up to the point of configuration 'freeze' and the decision to proceed with a detailed design and preparation of drawings for hardware fabrication. Figure 17 shows the duration of typical preliminary design activity in relation to the current DSARC and milestone reviews.

The AGARD Flight Mechanics Panel has long been concerned with aircraft design and technology integration. In recognition of the increasing concerns about rising system costs, the Panel, in October 1971, initiated planning for a meeting to review the role of the preliminary design process in improving quality and reducing aircraft acquisition and operation cost. The symposium on Aircraft Design and Optimization was conducted in October 1973 and results are published in AGARD Conference Proceedings, CP No. 147. During this meeting approximately 120 highly experienced aircraft designers, managers, cost experts, and operators discussed use of the preliminary design process and shared experiences, methods, and ideas for optimizing system characteristics and reducing cost of development, production, operation and support.

The process has evolved significantly over the years, and consideration is now given not only to the classical flight vehicle areas of aerodynamics, structures, propulsion, flight control, subsystems, and avionics, but also to other critical areas, such as maintainability, supportability, operational availability, and costs. Life cycle cost is now a basic design parameter, and the system characteristics must be decided on the basis of mission needs, performance capabilities, timing, and life cycle costs.

The preliminary design and development process includes numerous iterative paper and computer configuration and system analyses, studies and design layouts, supplemented by testing as necessary, to optimize trades between requirements, available technology, timing, and cost. Rapid progress in digital computers has led to a revolution in the use of computerized analysis and design techniques. These permit the examination of thousands of possible designs and clearly facilitate many trade-offs required to optimize the system capabilities and cost. Accuracy of analysis methods has improved steadily over past years, yet results of pure 'paper analyses,' sometimes used for decision making purposes, must be considered 'suspect' unless adequate assurances exist that the assumptions made in preparing the analytical model are fully valid for the new design being analyzed. Since the new design obviously includes configuration, flight environment, or operational usage improvements in order to warrant its development, it is likely that the analytical models which were developed and validated from previous design efforts will introduce some errors when applied to the new design. Thus, in contrast to 'paper studies,' the developmental tests involved in the preliminary design process provide a markedly different degree of confidence and progress toward a real airplane.

Key Tasks: Some of the numerous key basic tasks accomplished by use of the preliminary design/mission analysis process, both as a part of systems acquisition or prior to the identification of a system need are shown below:

1. Analysis of the threat and mission needs.
2. Analysis and trade-off of mission and system requirements with potential system capabilities.
3. Development and synthesis of systems options to meet needs.
4. Identification and resolution of system integration problems.
5. Design to consider manufacturing, operational deployment, and field support needs, and total performance time LCC trades.
6. Determination and assessment of technology, time, and cost uncertainties.
7. Identification of technical gaps or barriers requiring solution.
8. Assessment of the payoff from application of new technology.

Impact of Systems Development and LCC: The conceptual and preliminary design phase of a new system exerts a major impact on the subsequent system capabilities and cost. Figure 2 shows the leverage involved in this phase compared to the total development, acquisition and ownership cost of a new system. The preliminary design process in this case included synthesis of a large number of potential configurations and substantial wind tunnel tests, as well as design of the selected configuration. Yet, it constituted only a very small portion of the total life cycle cost of the system - less than one half of one percent (0.5%). Since this system is still operational, the percentage cost of the design portion is going down even further each year. Figure 18 which is familiar to many, points out that some 70 percent of the final life cycle cost of a system will essentially be predetermined by the system characteristics determined and the decisions made during the preliminary design process by DSARC I and 85% by DSARC II.

The early phase of the design process can be invaluable when used in conjunction with systems and operational analyses in assessing optional systems to meet mission requirements, impact of uncertainties, the payoff of new technologies, and the cost of achieving various levels of capabilities as a function of different scenarios. Trade-offs can be made to determine the best solution to the total set of needs. Later phases of the process define the total system design, test and contractual requirements in relation to all of the needs and technical, development, production, operational, support and cost considerations, and provide a basis for proceeding into the detailed designs for hardware fabrication and system hardware development.

Exploration of New Systems, LCC and Mission Effectiveness. The preliminary system design/mission analysis process can be highly effective in developing new system concepts and in evaluating optional solutions to projected mission needs in a wide variety of potential scenarios. The result can be a valuable asset in providing the foundation for the pre-milestone 0 activity by assessing needs and evolving concepts for solutions to both the military needs and reduced life cycle costs. (The pre-milestone 0 process, how-

ever, is not intended to express the need in terms of performance of a specific desired system.) The basic design process can be utilized as a valuable tool in identifying technical gaps and in assessing the value of R&D programs independent of the system acquisition process. Conceptual future systems can be developed on the drawing board and used as the basis for continuing interaction between the technologist and the military operators in evaluating new concepts and assessing potential solutions to operation needs.

Substantial progress has been made during the past decade in evolving the preliminary design process from one primarily associated with the flight vehicle system, Figure 16 to one that includes all aspects of a system and its development, manufacture, operation and support. The conceptual phase of the process has also evolved as an effective means of trading off mission capabilities vs systems characteristics and costs, and of evaluating the payoff of applying new technologies emerging from laboratory and industry research and development programs.

A major study program conducted several years ago utilized a combined operations analysis, threat scenario, mission need, preliminary design, and cost analysis process on an iterative basis to explore the relative merits of alternative system concepts and to assess the value of various arrays of new technologies. A schematic of one of the processes used is shown in Figure 19. Typical system options examined by this process as shown by Figure 20, were based on computer aided design methodologies to synthesize systems with many alternative mixes of new technologies, assess cost, and determine mission effectiveness against a wide variety of scenarios. This permitted an evaluation of both the new system concepts and technology mixes in terms of military mission criteria, such as cost for a target kill, number of targets killed for a given force strength or for a fixed investment in the new system, systems lost per target kill, and so forth. These studies also provided assessment of technologies in terms of the more conventional payoff criteria, such as aircraft weight, aerodynamic L/D, structural weight fraction, and system development, production and operational cost.

The higher order synthesis represented by the above process involves many complex and interdependent relationships. Credible outputs require probabilistic consideration of all significant parameters and identification of the sensitivities of the many inputs and assumptions made in the process. Increased complexity normally results in higher engineering and computer costs and a degradation in the ability to perceive all of the cause - effect relationships, and care must be taken to assure full consideration of the problems. Inclusion of methods to estimate combat effectiveness and cost as part of the basic sizing and performance analysis provides a direct relationship between mission effectiveness measures, costs and the basic design variables noted above. The number of variables which must be analyzed, understood and provided traceability in terms of their effect on the results is clearly increased as shown by Figure 21. When a large number of possible new technology sets and multiple mission scenarious are added to the problem, the number of parameters becomes enormous.

Reference No.20 notes that traditional parametric analysis becomes impractical, since a problem with only four variables requires 256 data cases and 16 carpet plots to determine the interactions between the variables. This reference discusses the experience of one major system contractor in tackling the kind of problem noted above and examining techniques for handling the large number of design effectiveness and cost parameters. After considering the high computational cost involved with direct numerical methods using constrained optimization algorithms, the author recommends an approach which employes multi-layering regressions for problem simplification. The use of computer routines for surface-fit regressions and optimizations, and multi-variable data management techniques were found to provide adequate accuracy during the conceptual design process, with a factor of 10 reduction in analysis cost.

Extension of the conceptual and preliminary design process with these types of analysis can be expected to result in the evolution of a number of effective techniques to handle higher order systems and LCC problems, simplify the effort, reduce cost per analysis and improve results. A major challenge is to fully exploit the ever increasing new computational capabilities, but at the same time not lose the understanding and innovation traditionally part of the design process when the engineer did it all.

Assessment of New Technology: Use of the preliminary design/mission analysis process provides a powerful method for assessing the value of new technology, both during and independent of the systems acquisition programs. It facilitates an excellent understanding of the interrelationships between mission capabilities, system performance and characteristics, key system parameters, and LCC. It can identify the value of new technologies and quantify the payoff of those having major impact on the system performance, cost and mission capabilities. The process can be applied to examine modifications of existing systems as well as potential new systems. Since the entire system design can be considered, this methodology provides an effective means of avoiding sub-optimization in the selection of new research and development programs. This is done by interrelating the value of the technology to the system design parameters by use of baseline designs with and without the new technologies. The design parameters are related to the system characteristics, cost, and in turn to system performance capabilities. Mission and operational analyses relate the system performance to both single and multi-system mission capabilities in different combat scenarios. It is thus possible, within the depth and accuracy of the analysis, to quantify the payoff of sets of technologies and new system concepts in terms of mission effectiveness criteria.

The degree to which technologies can be quantified is limited by the extent of the analysis, but the process generally will identify and quantify the technologies which exert a first order effect on flight vehicle size. It can also quantify technologies that are highly significant to mission success, for example a high resolution SAR to locate tanks under adverse weather conditions. The value of many other technologies will simply now show up in the mission effectiveness or cost analysis, even though qualitative judgments indicate that they do contribute to system and mission effectiveness or cost reductions. However, the process does provide an effective framework which relates the characteristics and effectiveness of optional system designs to the military mission needs for a number of different scenarios.

Use of this framework for more specific and detailed studies of technologies which do not show up as a first order impact provides a means of exploring and understanding their value in relation to the system designs and mission capabilities. The engineer developing a new flat plate digital display to replace the conventional cathode ray tubes now used in the cockpit clearly understands the reduction in installed volume and weight, and the improved reliability expected from the new display, but finds it difficult and expensive to examine impact on a system or mission capabilities. By use of the design and analysis framework noted above, he can use detailed cockpit layouts representative of those typical of a new system. With the more detailed study of the specific area, the payoff can better be quantified and related to the overall system characteristics and mission capabilities.

Opportunities Remaining: More recent emphasis on the front end of the acquisition process should result in increased preliminary design effort. Nevertheless, there are still many opportunities for increased use of the process to improve system effectiveness and reduce LCC. For one thing, continuous use of the conceptual design portion of the process, coupled with system analysis and application of new technologies will provide early identification of new system concepts, and provide an effective means of assessing the value of new technologies and the total cost impact. Further, one could select technology mixes in such a way as to markedly reduce cost. We have all heard of a control configured vehicle, (CCV). It's now time for a cost configured system (CCS)!

It takes time to think out and assess the best solutions to projected problems. The design/analysis process is very inexpensive in comparison to the cost of a new system, but it's initiation after the military need is validated gives relatively little time to fully understand the need and develop the best solution. Ideally, the spectrum of projected needs should be continually bracketed by analyses to provide understanding of the interactions between projected threats, possible system solutions, technologies and costs. Then, when the need is validated, a sound foundation exists for accomplishing the system design in a relatively short time. This would help reduce system acquisition time, as well as helping to avoid problems and reduce LCC.

VII OPERATIONS AND SUPPORT COST:

Some 60% of Air Force costs are now expended in the Operations and Support (O&S activity. Programs to reduce costs, as noted earlier, have recognized the importance of obtaining a better O&S cost data base as a prerequisite to the establisment of meaningful DTLCC objectives. Nevertheless, a number of specific quantitative requirements have been established for improvements in the O&S area. These include specific goals and quantities for maintenance man hours per flight hour (MMH/FH) and reliability improvement warranties (RIW's). Efforts are also underway to improve the data base and augment logistic research activities in order to improve understanding of the total process as projected over the next decade, and pave the way to the identification and implementation of specific actions to contain or reduce O&S cost.

O&S cost drivers are numerous, and range from the nature of the process itself to the operational characteristics and support needs of a specific system. A number of parameters which exert a significant influence on O&S cost are shown below:

- Logistics maintenance level and supply concept.
- Facility/spare part locations.
- Manpower skills/productivity.
- Numbers of systems to be serviced and maintained.
- Numbers of different weapons systems and separate part numbers.
- System characteristics, complexity and uniqueness.
- System inspection and test concept.
- System flying time and reliability/failure rates.

Understanding of cost drivers, such as above, is vital for the evolution of long term solutions. The logistic system is highly complex, and since some 40% of Air Force manpower are involved in the logistic process, it is highly sensitive to manpower, personnel and training systems, as well as the quality of the systems which emerge from the acquisition process. While many types of logistic studies have been conducted, the resources devoted to logistics research and development of a systematic understanding of the entire logistics process, and its interaction with the ever changing environment and all other factors related to the support of systems throughout their operational life, have only represented a very small percentage of the total R&D activity. As a result considerable

emphasis is being given to research of this area.

Higher Order Analysis: Computer analysis capabilities now make feasible the concept of a macro analysis, not just of a single system in relation to the O&S process, but of the total set of systems that exist at any one time. Such a 'higher order' analysis would also deal with the dynamic nature of the environment and the changing sets of systems and characteristics which exist as time passes. Such an analysis would provide greater recognition of both the common and unique activities associated with the different types of weapon systems and the support processes, and highlight the need for changes in the basic process. During acquisition, each System Project Office (SPO) includes representatives from the logistics and operational organizations in order to help assure full consideration of O&S needs. Trade studies to identify the best solution are of necessity forced to consider the O&S process and institutionalized procedures as they now exist. Unique system innovations are limited in their payoff to that possible within the constraints of the O&S process. Better understanding of this process will permit improved quantification of the key aspects relating to improved operational effectiveness and reduced O&S costs. This will pave the way for major improvements. Figure 22 depicts this concept.

VIII ADVANCED TECHNOLOGY

Use of advanced technology can reduce cost. In fact, it can both drastically reduce cost and greatly improve capabilities at the same time. The modern computer or hand calculator is clear evidence of this. Figures 23 and 24 show the striking progress in this area. If it can be done here, why not for complete weapon systems? Why not for the entire set of systems and processes? The answer of course is that revolutionary technical advances are not being made in all areas. Some are advancing rapidly, especially those that exploit the major advances in digital integrated circuit technology. Some are relatively mature, in need of a new breakthrough, but are advancing to some extent. The massive R&D program in progress throughout much of the world is advancing technologies on a broad front. The ability to recognize and exploit its application to the cost problem is perhaps the major problem confronting the use of new technology to reduce cost. One of the significant things about the computer revolution was the recognition and exploitation of the semi-conductor technology, and in turn, the continual development of semiconductor device technology to exploit the opportunities offered by the new market. Hopefully, the new logistics research activities now underway will help identify a similar mutual technology and market exploitation situation.

Reduction of total Life Cycle Cost (LCC), is a matter of much emphasis in the technology development program. Cost is considered to be a key engineering parameter and is given emphasis similar to performance. Most R&D programs reduce cost directly or indirectly, since improved capabilities should reduce the cost to accomplish any specific task. Reduction of cost to accomplish a military task does not, however, necessarily reduce the peacetime LCC. A missile can drastically reduce the number of missions or aircraft losses required to destroy a bridge in wartime, but missile development and acquisition represents a major slice of total peacetime acquisition cost, although their O&S costs is a smaller percentage of the total LCC.

Technology to Improve Basic Capabilities and Reduce Cost: Technology developments include many generic technology efforts to develop improved engineering tools, innovative concepts and experimental prototypes, and criteria for improved subsystems and systems. The engineering tools encompass technical prediction, design, analysis, and test methods, engineering handbooks and data compendiums, and criteria necessary for the efficient design of more effective systems. Some of this work is directed towards acquiring cost data and developing improved analysis methods. Innovative technology developments may apply to a wide variety of systems or be focused on more specific problems, for example, tactical fighter maneuverability. Other technology efforts are more sharply focused on specific aircraft or subsystem problems in order to improve effectiveness of systems in service or under development. The wide variety of new technology programs provide the basis for either improving performance capability or the many parameters that reduce LCC.

The choice depends on how the technology development is oriented and is applied in the system design or production and O&S area. As an example, new technologies can be utilized to reduce size or gross weight for the same mission, or improve mission capabilities for the same size aircraft. Even though shortages in the support of technical developments aimed primarily at reduced LCC have led to concern about the credibility of LCC reduction technology programs, many approaches have been exploited in an effort to reduce LCC. The development of improved engineering tools is aimed at reducing development and test cost and, to a growing extent, maintenance costs. Innovative structural concepts are being developed to utilize advanced materials in a more effective manner. New structure technologies, such as primary adhesive bonded structures of metals and advanced composites, eliminate thousands of the fasteners normally used in aircraft construction. This eliminates a prime source of corrosion and crack initiation, both expensive maintenance problems. Reduction of the number of parts in the structure helps reduce manufacturing costs. Structural design and manufacturing processes for advanced composites and titanium parts are aimed at the reduction of excess material waste by use of techniques which will form the parts close to the finished shape without extensive machining operations, thus also saving expensive machine time.

Similar concepts for reducing material wastage and numbers of parts are being exploited in turbine engine design by the development of technologies which reduce the number of

blades per compressor or turbine stage, and high flow technology which reduces the number of stages and the size of combustors. The simplifications made possible by advanced technology not only reduce costs, but improve engine efficiency and reliability.

In the avionics area, the utilization of large scale integrated circuits and advanced devices is improving the inherent reliability of avionics, and thus should reduce future LCC. Another major effort is aimed at the development of standardization with flexibility. Efforts range from development of basic device technologies to digital system architectures which will improve standardization of system elements higher order language (HOL) usage and associated software.

Thus, the basic concepts of simplification, reduction of numbers of parts, use of inherently reliable components, reduction of material scrappage, and standardization are providing significant opportunities for reduced LCC. These and other strategies for achieving reduced cost are shown on Figure 25 . Several of the many technology developments under way to directly reduce system life cycle cost and improve operational productivity are discussed next.

Manufacturing Technology: Aircraft cost is increased by the batch nature of aircraft production. Use of the computer as an aid to manufacturing has evolved in a disjointed fashion, resulting in a proliferation of computer software and hardware that has in many instances aggravated problems rather than assisting. A long term program has been initiated to apply integrated computer aided manufacturing (ICAM) systems for the major functions of manufacturing, in order to increase industrial productivity and flexibility for batch production of defense material. The program will first address the "architecture" and define batch manufacturing developments in the sheet metal fabrication area that promise high ROI's, on the order of 25% as a goal. Figure 26 shows the basic fields of activity now being pursued.

Engine Durability and Cost Reduction: Emphasis is being given to reducing engine maintenance costs and spare rates, and increasing combat readiness. Substantial progress is expected in improving the durability of engine structure and flow path components, the reliability of control systems, and the techniques for monitoring, automatically diagnosing and isolating faults to improve detection of potential failures, and to maximize engine life. Specific gains expected include (1) increased transonic blade aerodynamic loading capacity of rotating machinery to reduce the number of engine parts and minimize unit costs for competitive performance, (2) improved engine life prediction techniques and definitive criteria to upgrade design practices and relate performance growth to changes in maintenance costs and spare rates, (3) integration and simplification of aircraft/engine control modes to simplify field trim procedures and minimize maintenance down time, and (4) improved damage tolerant design practices, fault isolation techniques, and automated diagnostic techniques to maximize engine life and effectively apply "on condition" maintenance concepts.

Low Cost Titanium and Superalloy Engine Parts: It is currently necessary to buy approximately 20 times the raw material that ends up in a finished engine part, due to limitations in fabrication technology and the need to remove material in order to reach the required finished shape. A number of technology programs are aimed at improving this situation. For example, (1) titanium powder technology and powder metallurgy process developments, such as hot isostatic pressing, vacuum hot pressing, and powder consolidation, are being examined to provide a 30% cost reduction in titanium compressor discs, (2) technologies involved in automation of the directional solidification process, and scale-up of advanced coating processes are being applied to develop an improved manufacturing process that will reduce cost of directly solidified superalloy turbine airfoils by 40%, and (3) superalloy turbine disc technology development is aimed at reducing cost 50% through use of superalloy powder production techniques to produce near net shapes requiring minimal machining.

Avionics Device Technology: This fast advancing area provides the microelectronic, solid state devices, and circuit components such as magnetic bubble memories, high speed logic devices, charge transfer devices, amplifiers, etc. which underlie the major advances in computers and avionics. A major effort is aimed at the reduction of Life Cycle Cost through improved reliability, reduced size, weight and power requirements, and the development of commonality and standardization in utilization of microelectronics. Application of these devices includes virtually all aspects of aircraft avionics. Major thrusts are aimed at technology for large scale integration (LSI) very high speed integrated circuits, (VHSIC), logics and memories.

Cryo coolers required for use with IR detectors and other devices have been a source of frequent field problems. In addition, current coolers vary in type, thus complicating the maintenance problems. Advances in high reliability cooling technology have led to the development of a new standard cryo cooler based on the Vuilleumier design, which is unique in not requiring moving seals. It has a lower life cycle cost and a 10:1 higher MTBF.

Integrated Technologies Development of advanced integrated technology capabilities can exploit synergistic effects to reduce LCC. Identification of potential high payoff areas for technology integration is explored by study of existing and possible advanced systems. Sets of technologies offering potential high payoff and/or cost reduction are identified for demonstration to work out interactions and evaluate real capabilities.

Propulsion systems exert a major effect on system performance and on LCC. Progress in integrated turbine engine technology is graphically shown by Figure 27 which compares thres generations of engines each having approximately the same thrust. The 8:1 thrust ratio of the F-100, F-101/F-404 class engines represent a 100% improvement over previous fighter engines. Projected engines show 11 to 12:1 thrust to weight ratios.

Some of the concepts being investigated and developed at the component level were noted earlier. When these and others are combined in a new engine, the result can be improved specific fuel consumption with reduction of mechanical complexity, e.g., (1) fuel consumption will be reduced both at the high thrust settings for maneuver and the lower settings for cruise flight. As with aircraft, the engine designer can utilize the new technology in a variety of ways to maximize the performance or other characteristics that are most important. In some 10 years, technology will permit the designer to choose either significantly improved performance or reduced LCC or some of both. Improved LCC choices are projected to include the following:

1. Thrust specific fuel consumption (SFC): 5% to 10% improvement by reduced turbine cooling air, improved seals, increased efficiency nozzles, improved component efficiency, reduced loss combustors, variable cycle concepts, etc.
2. Life Cycle Cost (LCC): 20% to 30% reduction due to reduced number of parts, improved durability, and improved fabrication technology.

The YF-16 prototype development utilized a number of technical approaches and some advanced technologies selected to reduce cost, as shown on Figure 28. While sufficient operational experience is not yet available, some of the new technologies such as advanced composites and the fly-by-wire flight control system were expected to both improve performance and reduce O&S costs.

Effectiveness of New Technology in Improving Logistics: Many examples clearly demonstrate that new technology can be effective in improving the O&S situation. In addition to its use during the acquisition process, new technology can be applied either to aircraft and missile systems to reduce their O&S costs or to the logistics process itself in order to improve servicing, maintenance, supply, and decision-making capabilities.

It is well accepted that the best time to apply a new technology is during the initial systems design and development phase. The many advanced technologies which have been successfully applied to new systems during the early part of the acquisition process include some of importance to the O&S arena, as shown below:

Solid State Avionics

Digital Processors/Computers

Structural Fatigue Design Criteria

Advanced Manufacturing Technology

Fly-By-Wire Flight Control

Advanced Standardized Communications and Inertial Components

Low SFC/High By-Pass Turbo Fan Engines

Oxygen Concentrator

Samarium Cobalt Electric Generators and Motors

Constant Frequency Variable Speed Alternators

Technologies Applied Directly to the O&S Arena: Advanced technologies have also been successfully applied directly to the O&S arena, either to systems or to the logistics process. Despite the likelihood of higher costs in applying new technology during the O&S phase of a system's life, experience shows that new technology can be cost effective in alleviating expensive problems and improving operational effectiveness. This experience is validated by a series of successful application of Laboratory technology to the O&S arena by direct interaction between the Laboratories and associated Air Logistics Centers. It is further validated by the experience of the Productivity, Reliability, Availability, Maintainability (PRAM) Program Office which was established to mount a concerted attack on rising O&S costs. If major technology advances occur subsequent to the development of the system, the only means of using the technology to improve the system is by a modification or retrofit program during the O&S phase of the system. The planned B-52 and F-111 avionics updates are recent examples of this.

While many barriers must be overcome in transitioning Laboratory technologies directly into the O&S arena, many examples can be cited of solutions to a logistics/operational problem or need. Some of these represent application of available technology to solve very specific problems. Others represent improvements made possible by major technological advances which occurred subsequent to acquisition of the system. Some do both. Examples include

- Honeycomb Bonded Repair
- Structural Corrosion Reduction
- Standard Electronic Modules
- Fuel-Use Reduction
- Superalloy Vane Repair
- Bird Resistant Windshields
- NDI/NDE
- High Adhesion Sealants

Standard Cryo Cooler

Disc Retirement Extension

Development of compact standard electronic modules to replace older vacuum tube modules reduces the reliability problem, and provides enhanced capabilities made possible by advanced solid state avionics. Introduction of standardized avionics components and architecture will reduce part stocking requirements, improve interoperability, simplify maintenance and training, and enable more rapid modification of avionics systems without requiring major changes in the existing system.

Other programs are underway to reduce aircraft drag and thereby reduce the quantity of fuel required to perform any specified mission. The ten-fold rise in fuel cost since 1973 now makes conservation increasingly important. By example, the winglet program now underway is expected to improve the fuel economy of the KC-135 by some five to seven percent, with payback of implementation costs in less than two years. A number of other programs, such as advanced bonded structural technology and airframe design concepts are expected to yield significant acquisition and maintenance cost reductions during aircraft production by reducing the number of parts. The improved fatigue and corrosion resistance offered by several of these technologies will further reduce support costs.

The importance of a dedicated source of funding and management is well illustrated by the experience of the PRAM Project Office, which adopted a very stringent criteria; namely, that a project or a new technology must offer a 5:1 improvement in "Return on Investment (ROI)" within five years to warrant funding. Examples of numerous projects involving application of Laboratory technologies, which have been funded all or in part by this office, include:

- Automatic Trim Balancing
- Plasma Spectrometer
- Coldworked Hole Tool
- Electrostatic Airless Painting of Aircraft
- Lubricant Inventory Reduction
- Combined Environmental Reliability Testing
- Vibration Damping Material for Engine Inlets and Fan Cases
- Aluminum Surface Preparation for Bonding

A net savings of $117M for a PRAM cost of $5.7M is extimated for twenty of the PRAM/Laboratory projects which have been started. These do not include the major saving expected from application of the Combined Environmental Reliability Testing (CERT) Program which is still in progress, but has already contributed to improving O&S reliability operational hardware.

The CERT Program, for example, provides techniques and criteria for ground testing avionics equipment under the combined environments which the avionics are expected to encounter during flight. Tests are currently being conducted to validate the concept by comparing actual field experience with the results of current MIL SPEC and CERT tests. CERT test conditions simultaneously simulate the temperature, vibration, humidity, pressure, and power spikes expected during missions on a flight-by-flight basis. Results permit identification of failures and failure modes so that avionics systems can be improved before entering full service and will also provide a basis for more accurate provisioning of spare parts. CERT has already proven of value by its use to evaluate avionic equipments as part of the competitive selection process.

Additional Technology and Applications Needed: The fact that technology can significantly help in providing a solution to many O&S problems, and the impressive set of technology developments now underway, might lead to the belief that all that is possible is being done. This would be far from the truth. The current program represents only a fraction of that required to remedy the current situation and exploit the cost benefits possible through new technology. It a large problem. Clearly a long term continuous effort is needed.

Identification of the most pressing needs for logistics technologies is periodically updated and provided the system organizations. This includes both generic and specific needs. The generic needs tend to cover the more basic and long-term needs judged by AFLC/ALD to be of major importance for reducing logistics costs. More basic needs include research on logistics processes, procedures, and concepts to improve understanding, methodologies, trade-offs, and decision making, including the effects of technology and the changing world environment of the future in all areas of O&S. Other thrusts are aimed at improvements in Air Logistics Center maintenance and modification technology.

A number of new or augmented technology thrusts would provide significant improvements to the O&S process and LCC. R&D activities are underway, but in general is grossly insufficient in relation to the need or potential payoffs. Examples of several of these are

- Logistics research
- Global O&S Simulation
- Global LCC Models
- Manpower Productivity & Cost
- Automated Manufacture & Repair
- Fault Tolerant Systems
- Software Cost Reduction
- Material Deterioration/Corrosion prevention

A higher order analysis process, considering the total mix of systems, maintenance and support process is needed to develop an understanding of the complex multi-dimensional relationship that exists in the O&S or LCC area.

IX LIFE CYCLE COST DATA BASES & COSTING METHODS

LCC Data: Valid costing is an essential prerequisite for a true DTLCC program. O&S data base deficiencies have been the subject of many recent reviews in order to identify corrective actions. Although many inadequacies exist, and clear allocation of institutional and process costs to specific systems remains a difficult task, much data is available in the Air Force data base, if one knows how to obtain it and can spend the time necessary. Figure 29 shows typical maintenance data, for cargo aircraft, obtained from the Air Force 66-1 data system, which has been in operation for many years. Examples of the extensive data available on hardware maintenance and supply factors are shown by Figure 30. Such data is available in great detail on all aircraft, and provides specific information for all major subsystems and compliments. Figure 31 shows the breakout of the total 15 year LCC for a cargo aircraft by major categories based on the 66-1 data system and the existing Air Force CACE model, modified to a total fleet configuration. While much data can be extracted from the current system, efforts to improve its accessibility and completeness are of major importance. Improved data on processes and sequences will permit an improved understanding of the support flow-through process. Much data is currently available on the micro aspects of the process, but a macro analysis would greatly improve the ability to put it all together. This need is recognized, and the logistic research activity underway should improve the situation.

The acquisition cost data base, while not receiving as much recent concern as the O&S data base, also requires improvement. Here the problem is made more difficult by the proprietary interests involved, and difficulty in assessing the cost of introducing new technology.

Life Cycle Costing: Credible techniques are a key to the use of LCC factors in the decision process, especially when funds must be expended now to obtain a future cost benefit, and no other major associated benefits have been identified.

Much attention has been given to costing methodologies and the data base required for their development and validation. Most attention has been focused on the production process, and on analyses to provide insight into questions of limited scope, for example the cost/benefit of replacing titanium fastners with steel or aluminum, etc. Some 2000 logistics models are currently documented in the Defense Logistics Study Information Exchange. Most are aimed towards answers that require the type of information not available until the system is well along in the full scale development or production phase. Further, deficiencies in an effective mechanism for feedback and update of system O&S characteristics greatly impedes improvement of these models. There has been a long time need for techniques that relate material characteristics, fabrication, production methods and technology areas to the measured categories of cost. There has also been a lack of effective models for use during the conceptual and advanced development phases of a system acquisition.

The importance of costing has led to the establishment of organizations and continuous activities in the Air Force Systems Divisions, Logistics Division and Laboratories to develop improved costing methods. The ASD has long had and gradually augmented a capability for costing system development and production. The Air Force Wright Aeronautical Laboratories have, for much of the past decade, been actively engaged in developing improved methodologies and techniques for system and subsystem development and production costs. Efforts to analyze the O&S cost drivers were initiated by the laboratories in the early 1970's. Figure 30 shows a typical result that was used to identify technology developments offering high O&S payoffs. These led to follow-on efforts to identify unique cost differences between military versus commercial practices. This was followed by programs to evolve system development cost engineering relationships (CERs).

A continuing need exists for life cycle cost assessments on a quick reaction basis. ASD had devised a life cycle cost model programmed for a TI-59 hand held calculator to meet this need. By use of this analysis tool it is possible to assess the life cycle cost implications of specific alternatives easily and quickly. The model is as complete as most computer LCC models. Concentrating on a single item, such as a line replaceable unit (LRU) or shop replaceable unit (SRU) significantly reduces the need for memory capability and avoids the aggregation and control coding required in larger system models The model includes the major cost elements contained in a LCC assessment, as shown by the analysis working sheet in Figure 32.

During the past few years, progress has been made in quantifying life cycle costs engineering relationships (LCCERs). Figures 33 and 34 provide a view of the basic model organization typical results, and correlation with system cost data. Much still remains to be done. LCCERs need to be extended to the subsystem component level to enable engineers to make better trade-offs during the design process. The impact of new technology must be factored in with more realism, and unique design related aspects, such as the significant difference in reliability of the same avionics set installed in one location of an aircraft versus another location must be accounted for. The model is now limited to the system component level. Yet correlation is good, and the model should provide a much needed tool for use during preliminary design.

In the meantime, system cost projections are still made primarily on the basis of comparative data obtained from the development and production experiences with similar systems. Utilization of new models, such as that noted above is being examined, but more assurance of validity will be required for a change to be made.

X CONCLUSIONS:

Substantial attention has been given to the problems posed by the continuous rise in systems development, acquisition, operational and support costs. Actions are underway on both major cost drivers and on the innumerable specific cost problems that exist in the total LCC problem.

The prime focus of OMB/DOD efforts has been on improvements to the acquisition strategy and procurement process, with emphasis on DTC goals, related reliability and maintainability goals, and logistics support concepts to minimize costs. During the past several years, much emphasis has been given to reducing ownership costs, a significant new organization has been established, and logistics research efforts are being implemented. New concepts, such as the high-low mix, have been utilized to reduce the cost of new system acquisitions.

Significant progress has been made in developing the preliminary design/mission analysis process as a powerful tool for the exploration of new system concepts, the assessment of new technologies and concurrent analysis of life cycle cost implications, in addition to its use as a vital, high leverage step in the acquisition process. This process provides a superb learning opportunity and enhances communications between all involved in the system development, acquisition, operations, and support activities. Extension of the process for higher order analyses to examine concepts for improved interoperability, 'flexible standardization' of avionics, improved O&S effectiveness, and logistics research should provide significant life cycle cost savings if properly implemented. Selective use of advanced technologies and system designs to reduce life cycle cost should also be a target of such analyses. The process offers significant advantages in providing a continuous set of potential solutions to the ever changing threat and sets of national needs, and can save considerable time in fielding a new system after the need is identified and validated.

Development and application of advanced technology can result in significant reductions of LCC. Many technologies can be applied to either improve performance or reduce costs. A skilled designer can exploit the opportunities offered by advanced technologies to achieve many combinations of performance improvement or of cost reduction. The choice is his. Additional emphasis on developing those technologies which offer high payoffs in reducing costs would provide further options to the designer and should be given more attention in research and development programs.

Many technical cost, and mission need uncertainties will always be with us. We will never resolve them all , because in a dynamic world new ones will always be evolving, however it is most important to recognize their existance and plan accordingly. The use of rational margins for error in use of new technology and in LCC analyses is a must. Allowance for growth capabilities to handle emerging new needs is also a must.

The numerous basic impediments to attain a minimum life cycle cost, such as noted on Pages 1 and 2 require continual and concerted effort to resolve the problems. We are dealing with a very complex problem of 'cosmic' dimensions. Until the basic impediments are solved, the best course of action appears to be to press for implementation of the major opportunities that exist, and continue efforts throughout the system in improving awareness of the need and effort on all aspects of the problem that will reduce cost. Like the answer to the question, ' how does one eat an elephant?' the answer here too appears to be 'one bite at a time'. Hopefully the job can be accelerated if everyone works at it continually.

To quote Denham, "When any great design thou dost intend, Think on the means, the manner and the end."

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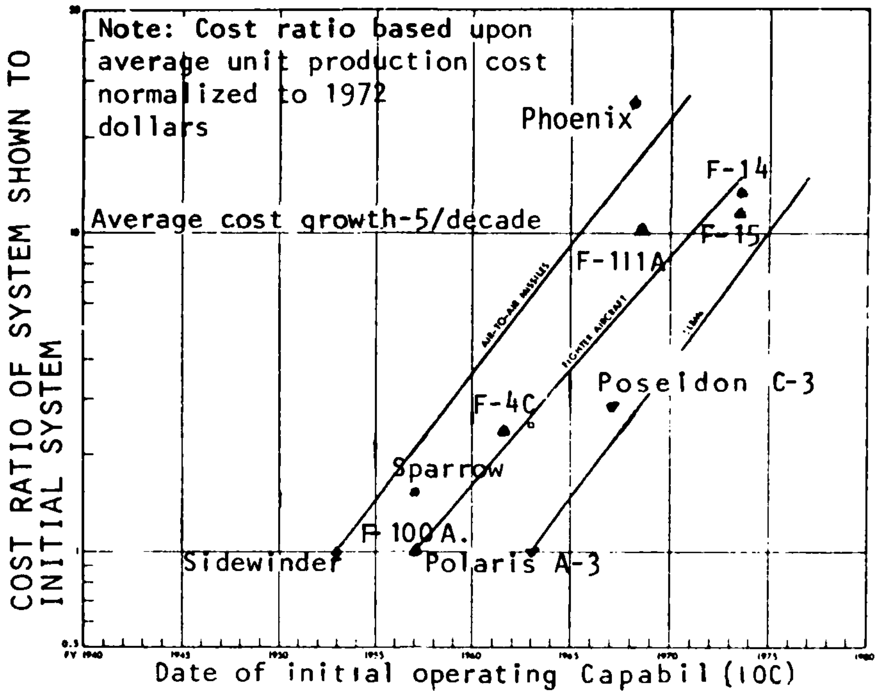
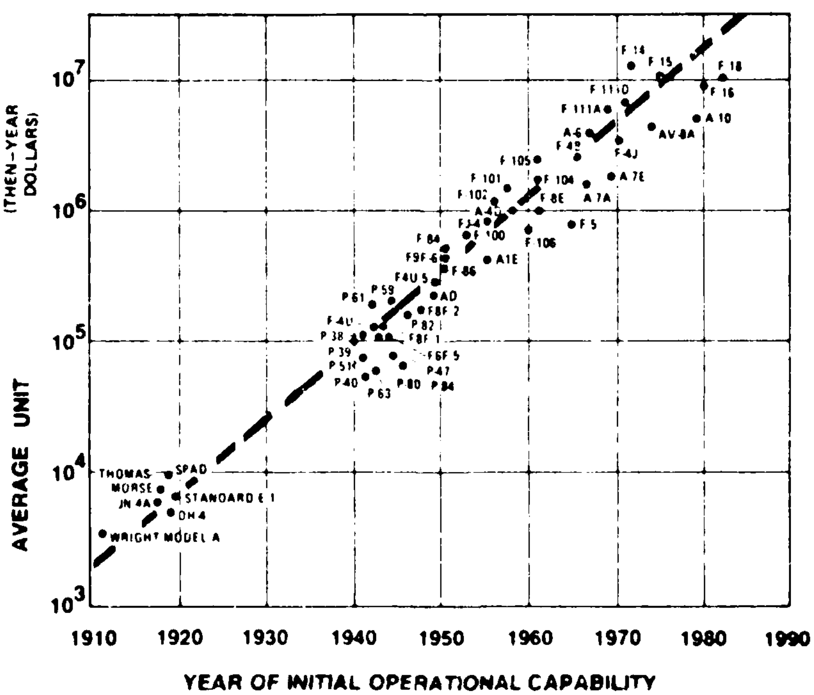


SYSTEM
NEW-GENERATION COST PROGRESSION FOR SYSTEMS

Figure 1A



INCREASING COST OF TACTICAL AIRCRAFT

Figure 1B

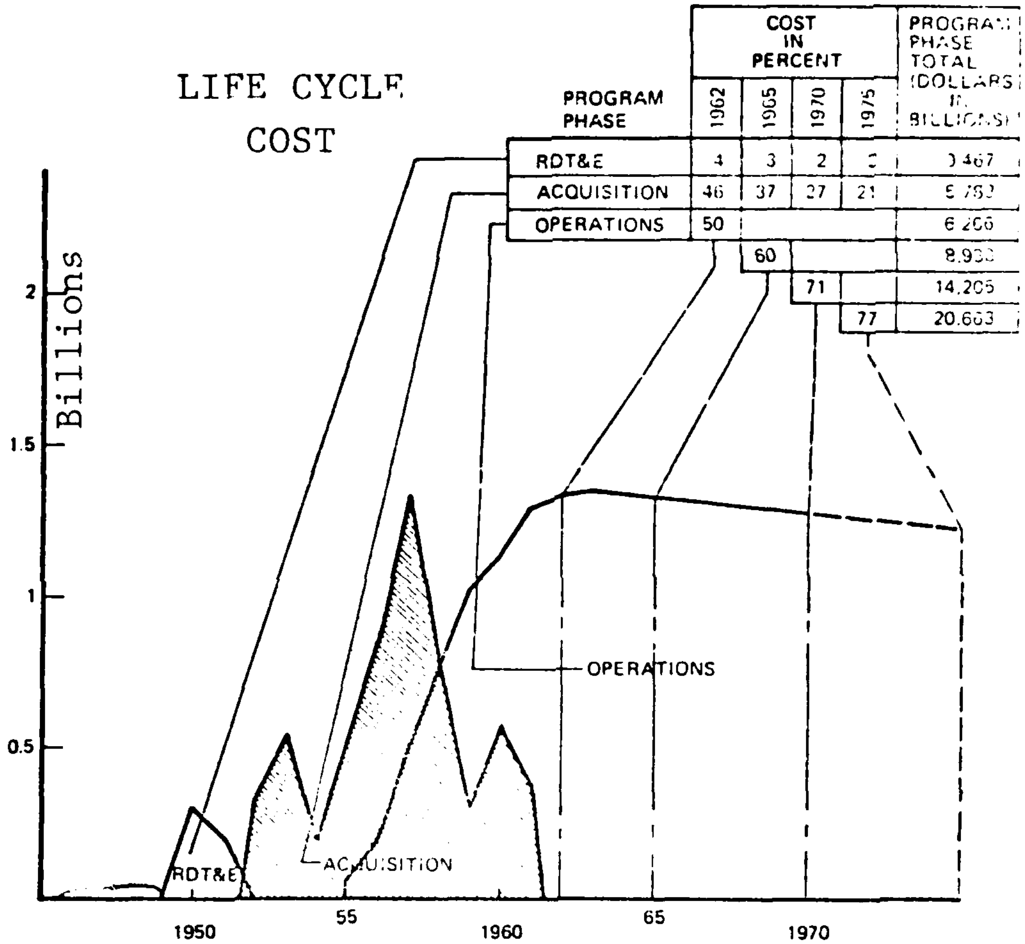


Figure 2

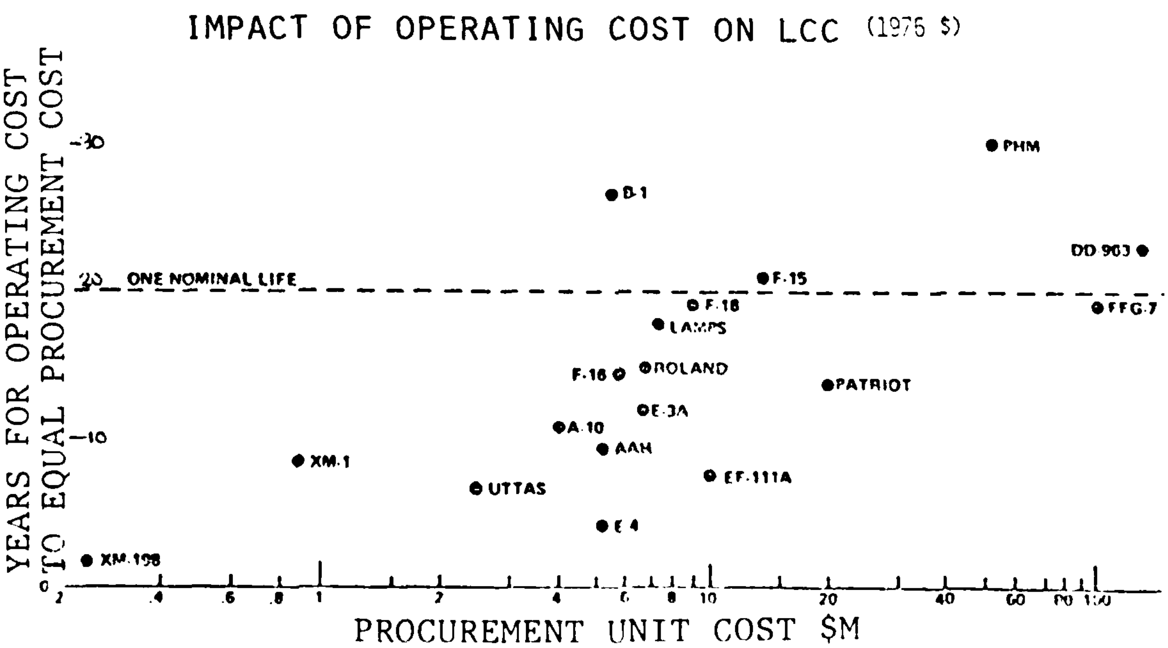


Figure 3

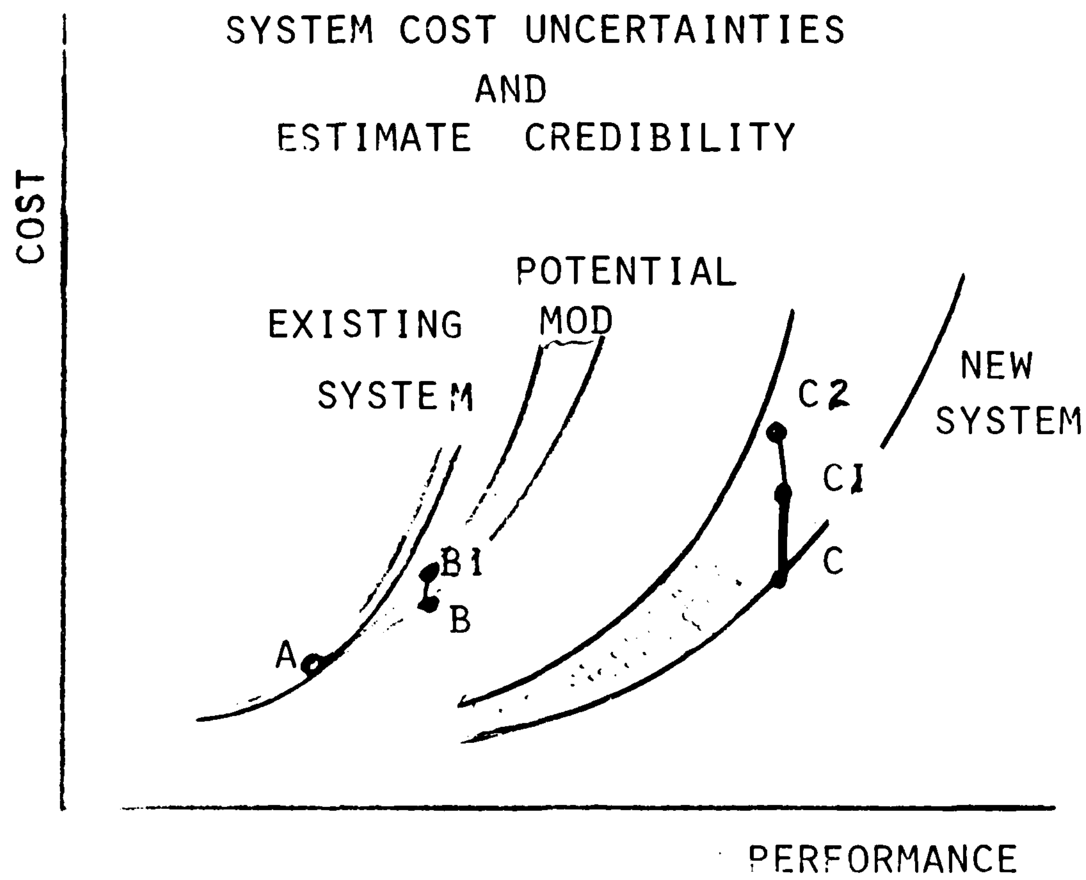


Figure 4

SOME
PAST COST REDUCTION METHODOLOGIES

- SYSTEM INTEGRATION
- MILESTONING
- SKUNK WORKS
- ADAPTIVE MANAGEMENT
- CONCURRENT DEVELOPMENT

- LIFE CYCLE COST
- DESIGN TO COST
- PROTOTYPING
- SHOULD COST
- FLY OFF
- FLY BEFORE BUY
- COMMONALITY
- "ILITIES"
- TOTAL PACKAGE

Figure

SYSTEM PROGRAM PHASES

PHASE	0	1	2	3
AIR FORCE 1960's & EARLY '70's	CONCEPT FORMULATION	CONCEPT DEFINITION	ACQUISITION	OPERATION
	EXPLORATORY & ADVANCED DEVELOPMENT	SOME HARDWARE DEVELOPMENT PAPER STUDIES		

CONDITIONAL APPR FOR DEV — RATIFICATION OF APPR FOR DEV

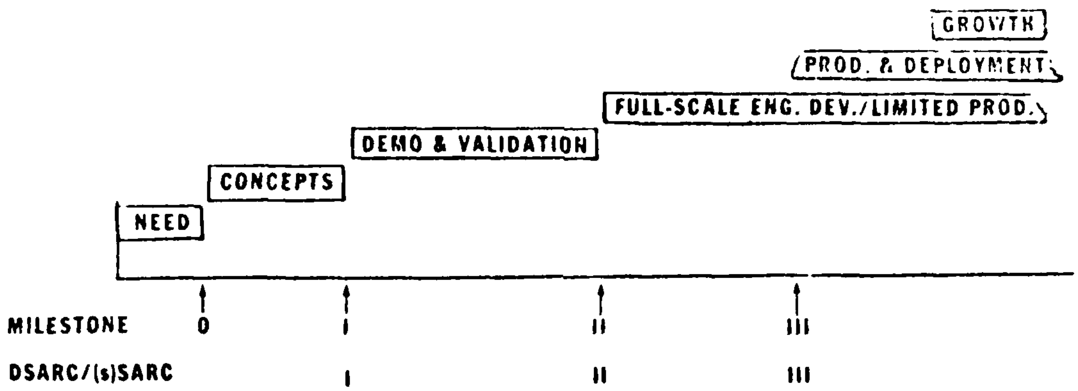


Figure 6

LIFE CYCLE COST

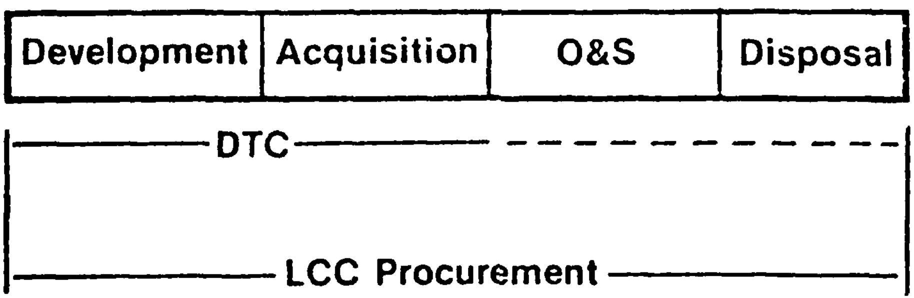


Figure 7

CDR'S LETTER MARCH 1975

- AFSC IS RESPONSIBLE FOR DEVELOPMENT AND APPLICATION OF TECHNIQUES AND TOOLS TO MAKE LCC A PRIME CONSIDERATION IN ALL OUR ACQUISITION PROGRAMS.
- WE MUST MAKE LCC OUR NORMAL WAY OF DOING BUSINESS.

  LCC IS THE TOTAL COST. IT INCLUDES COST TO DEVELOP, ACQUIRE, OPERATE AND SUPPORT AN ITEM, SUBSYSTEM, OR SYSTEM OVER ITS USEFUL LIFE.
- THE IMPORTANCE OF LCC IN DECISION MAKING MUST BE STRESSED.

Figure 8

AN OVERVIEW OF SYSTEM ACQUISITION

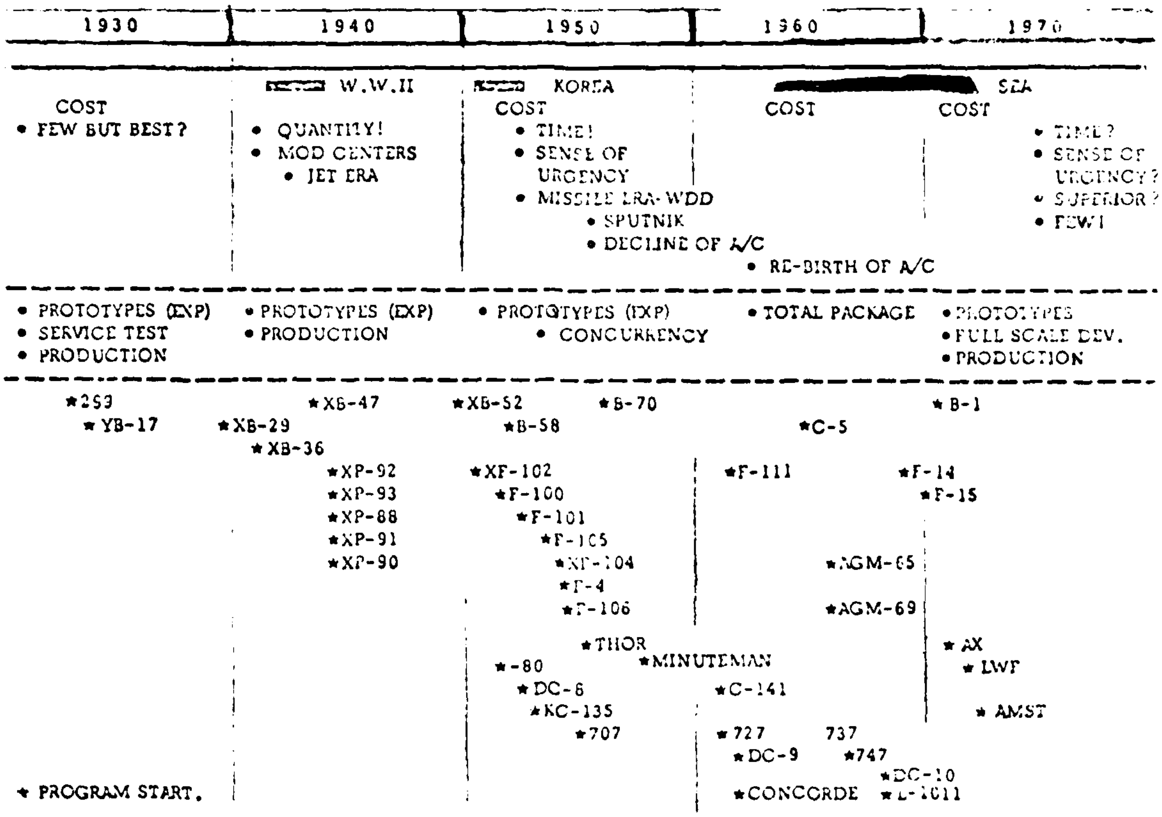


Figure 9

WHAT IS THE MINIMUM COST APPROACH ?

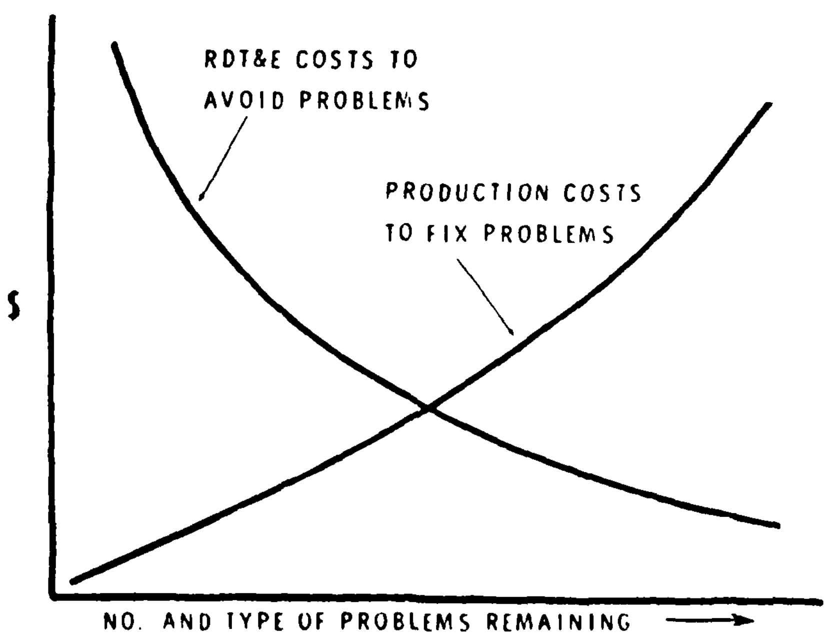


Figure 10

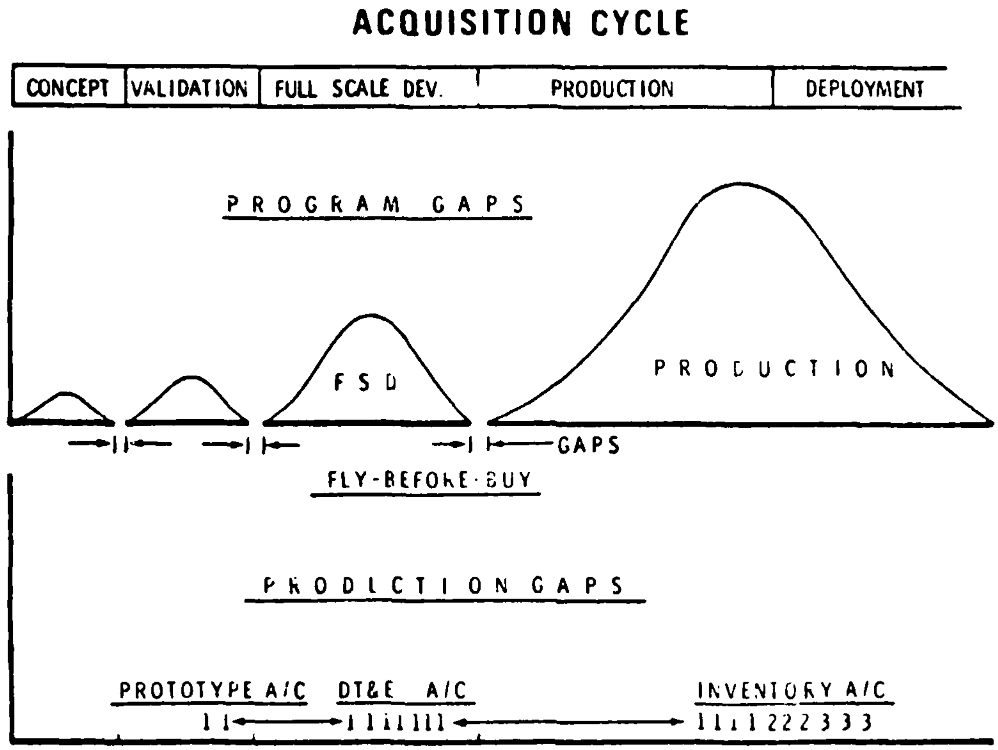


Figure 11

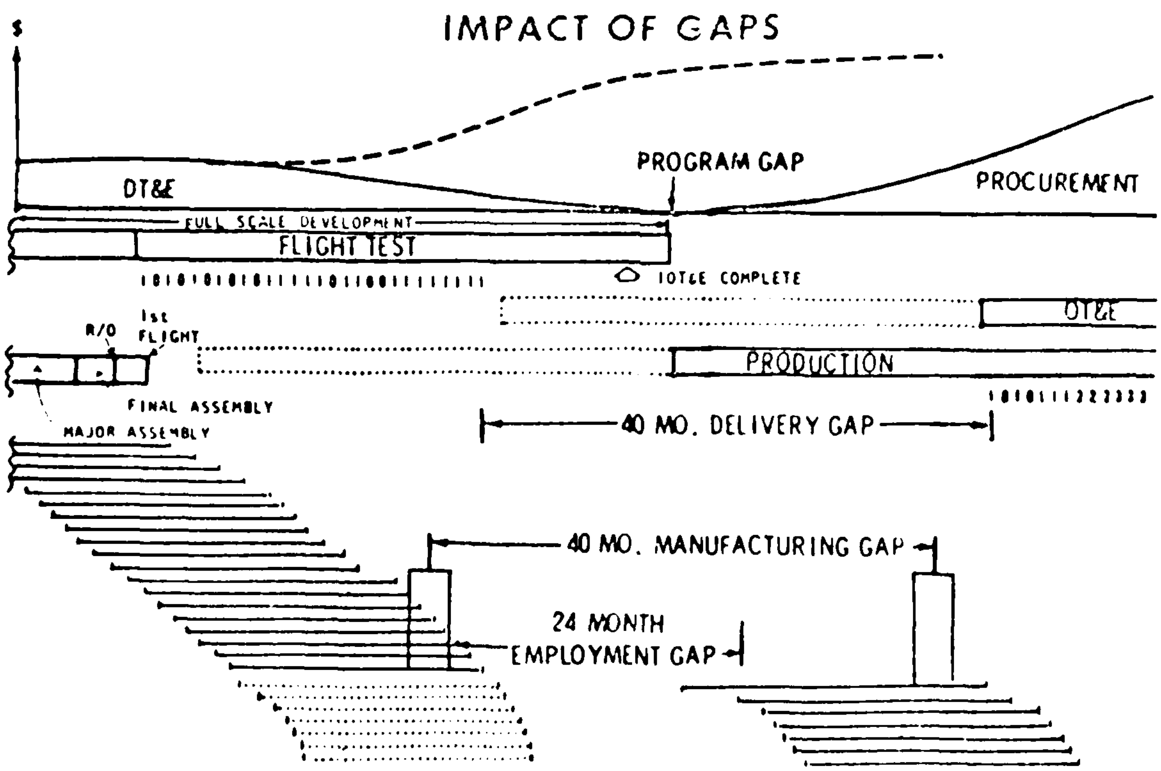


Figure 12

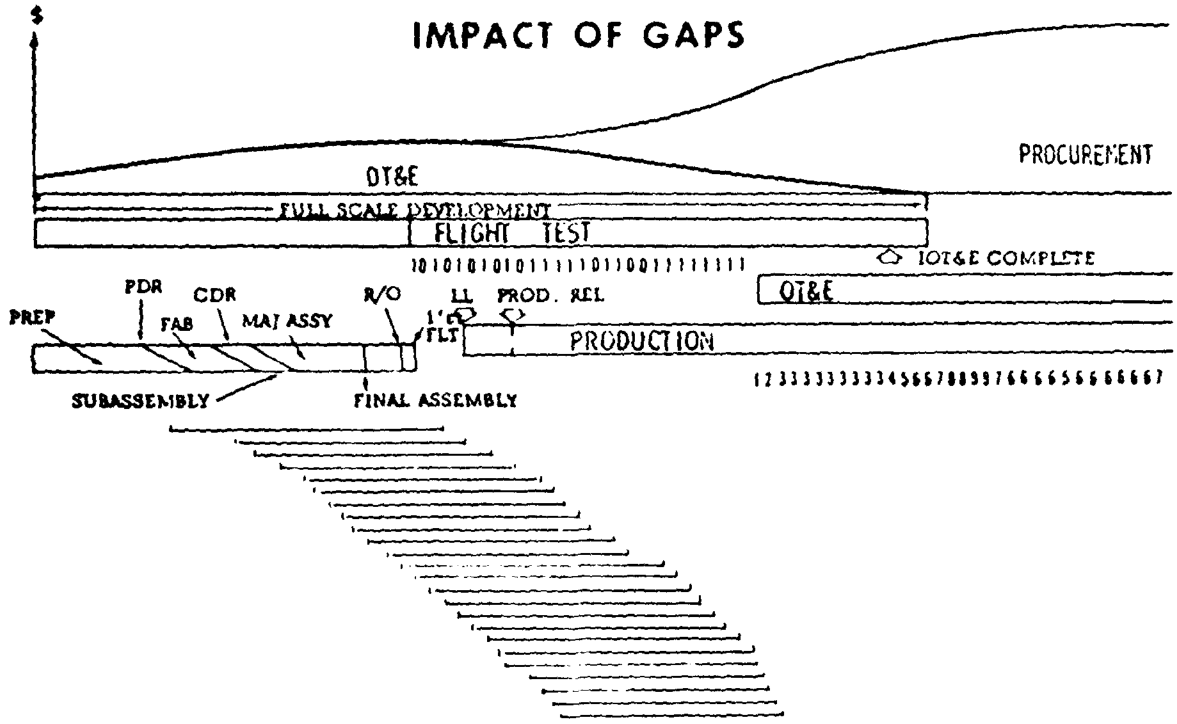


Figure 13

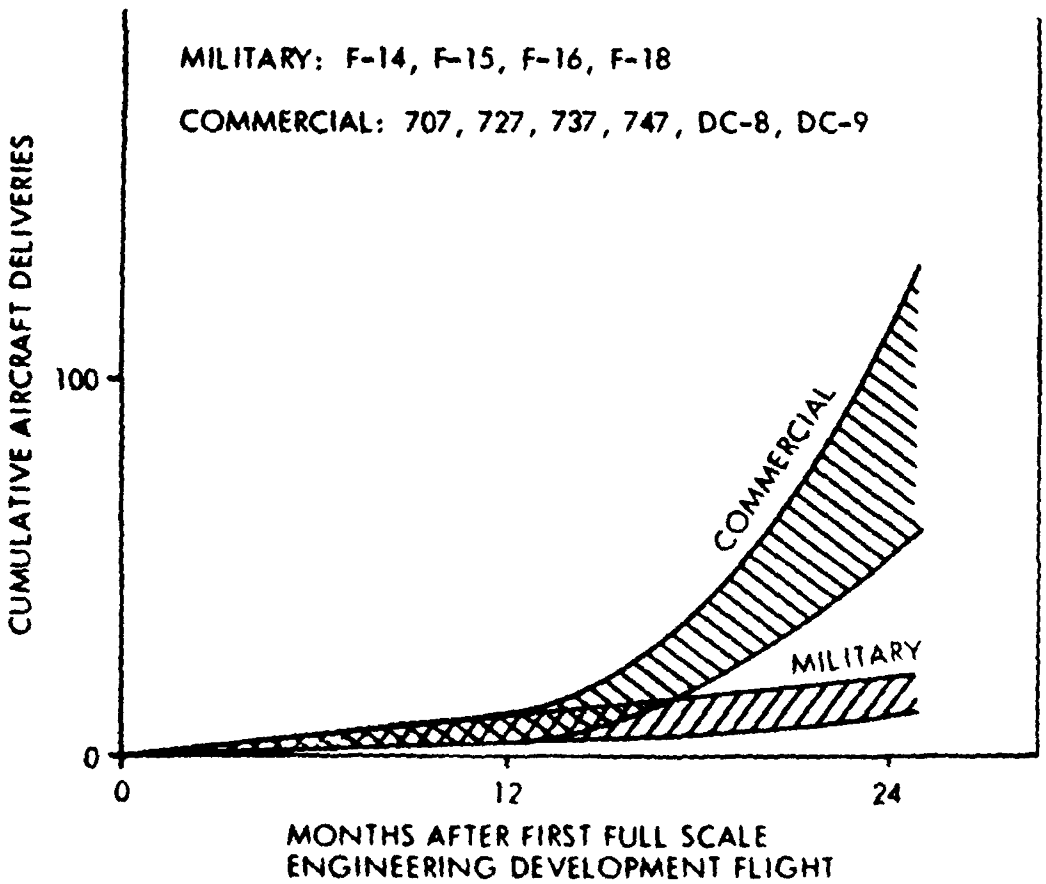


Figure 14

COMMERCIAL JET TRANSPORTS

SYSTEM	NR. TEST A/C	MOS. FROM DEVELOPMENT START TO FIRST FLIGHT	MOS. FROM FIRST FLT. TO FAA CERTIF.	CUMULATIVE AIRCRAFT AFTER FIRST FLIGHT 12 MO.	24 MO.	36 MO.	48 MO.
707	3 & -80	27	8+	10	82	173	252
727	4	29	10	6	101	212	346
737	6	26	8	4	111	223	260
747	5	35	10	4	96	165	195
DC-8	6	36	15	7 *	52 *	117 *	147 *
DC-9	5	24	9	10 *	79 *	234 *	634 *
DC-10	5	28	11	5 *	19 *	71 *	128 *
L-1011	5	32	16	3	18	52 *	-
CONCORDE	4	75		2	2	3	4
CITATION		17	6, 25	2	8	53	125

NOTES:
- PRODUCTION DECISION IMPLICIT IN DEVELOPMENT GO-AHEAD
- FAA CERTIFICATION USUALLY INITIATES AIRLINE SERVICE
- BAC-707 PRECEDED BY 1 PROTOTYPE MODEL 80

* ESTIMATED

Figure 15

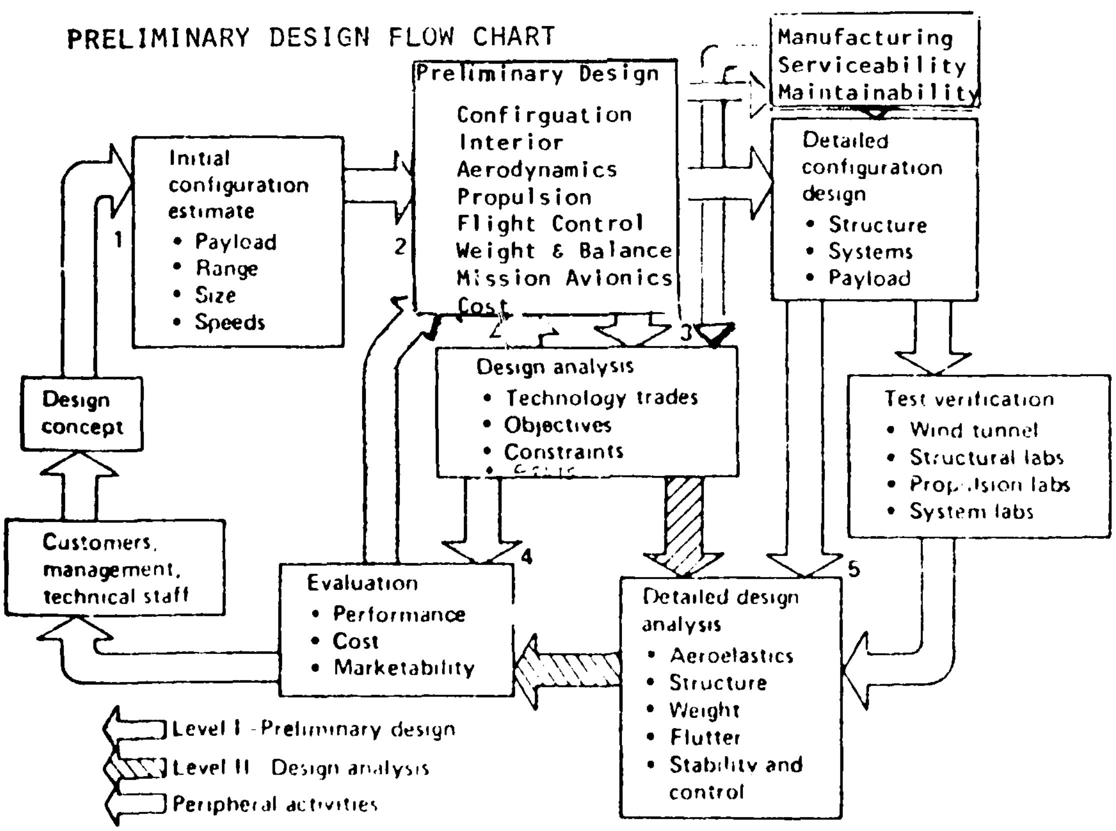


Figure 16

SYSTEM PROGRAM PHASES/PRELIMINARY DESIGN/DEVELOPMENT COMPARISON

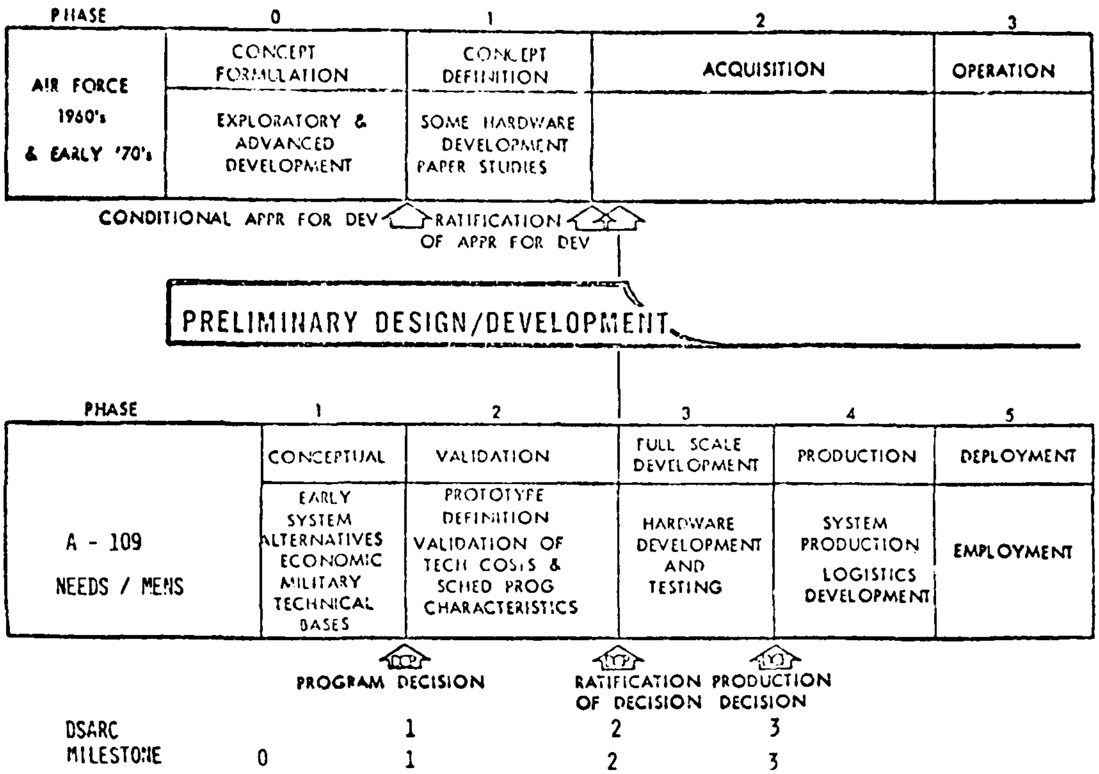


Figure 17

LIFE CYCLE COST DECISIONS

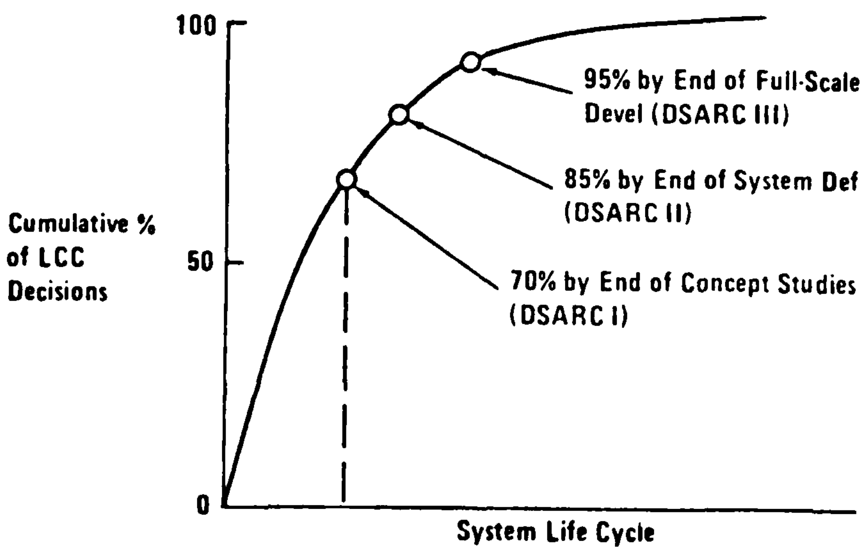


Figure 18

THE PROCESS

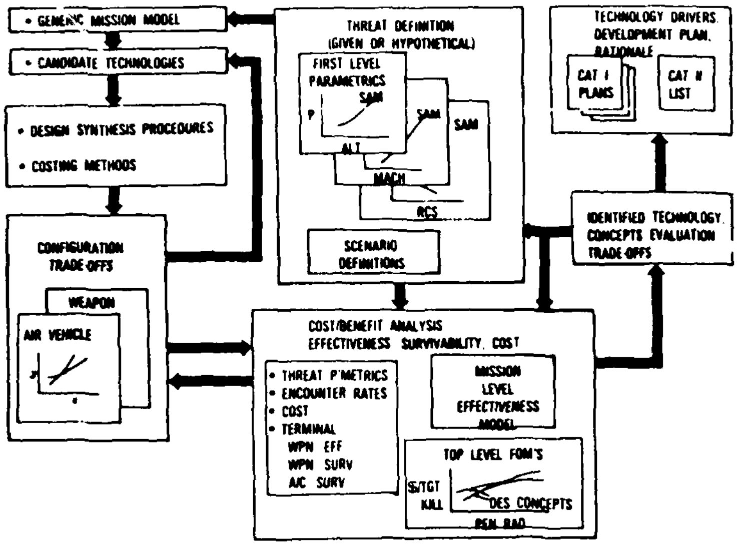


Figure 19

ATS STUDY AIRCRAFT CONFIGURATION BASELINES

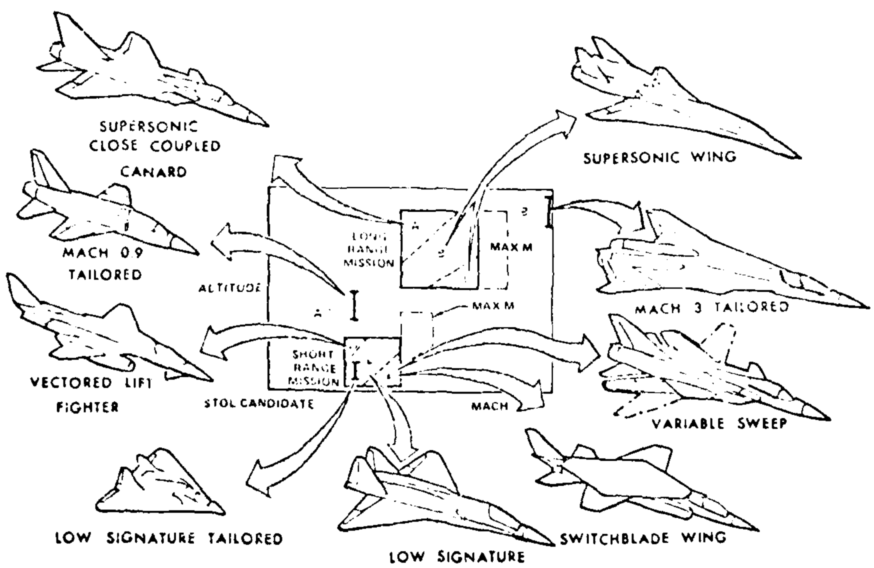


Figure 20

INDEPENDENT VARIABLES

OPERATING WEIGHT EMPTY, lb
MISSION RADIUS, nmi
TAKEOFF DISTANCE OVER 50 ft OBSTACLE, ft
APPROACH SPEED, kn
LANDING GROUND ROLL, ft
SURVIVABILITY g's
PROBABILITY OF SURVIVING AN ENCOUNTER
PROBABILITY OF SURVIVING MISSION
COST PER TARGET KILLED
ACQUISITION COST, $
FLYAWAY COST, $
FLEET LIFE CYCLE, $
MAXIMUM SUSTAINED g's

Figure 21

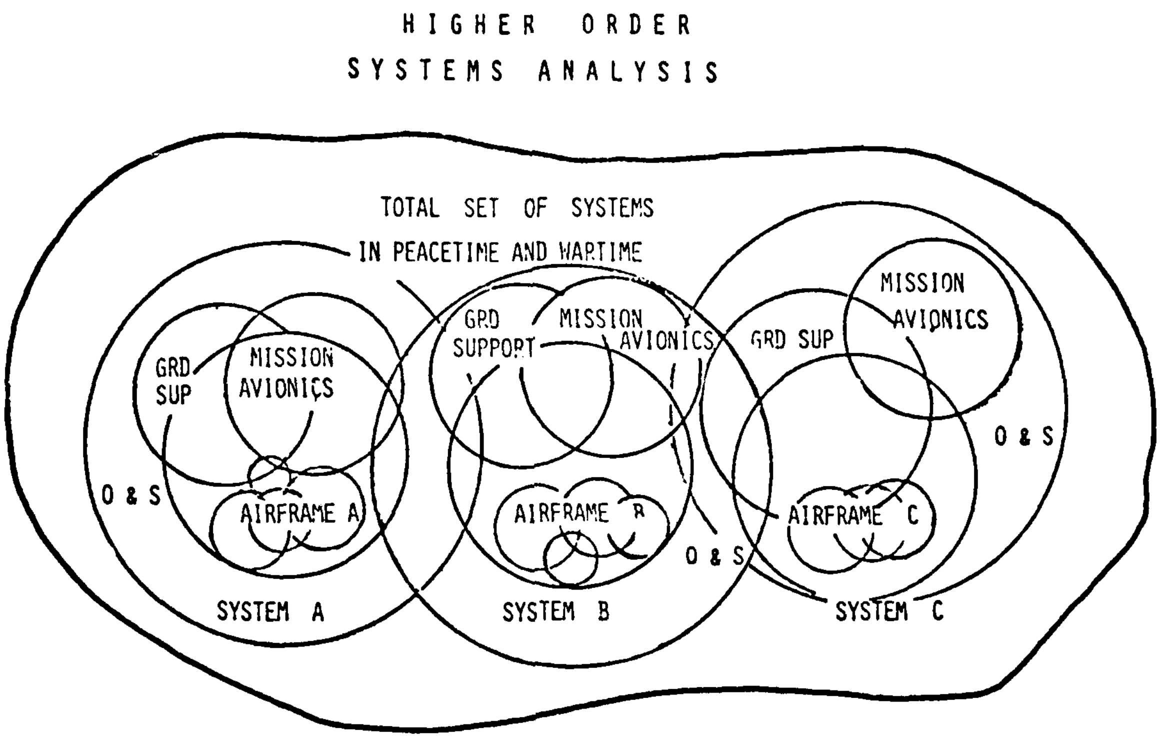


Figure 22

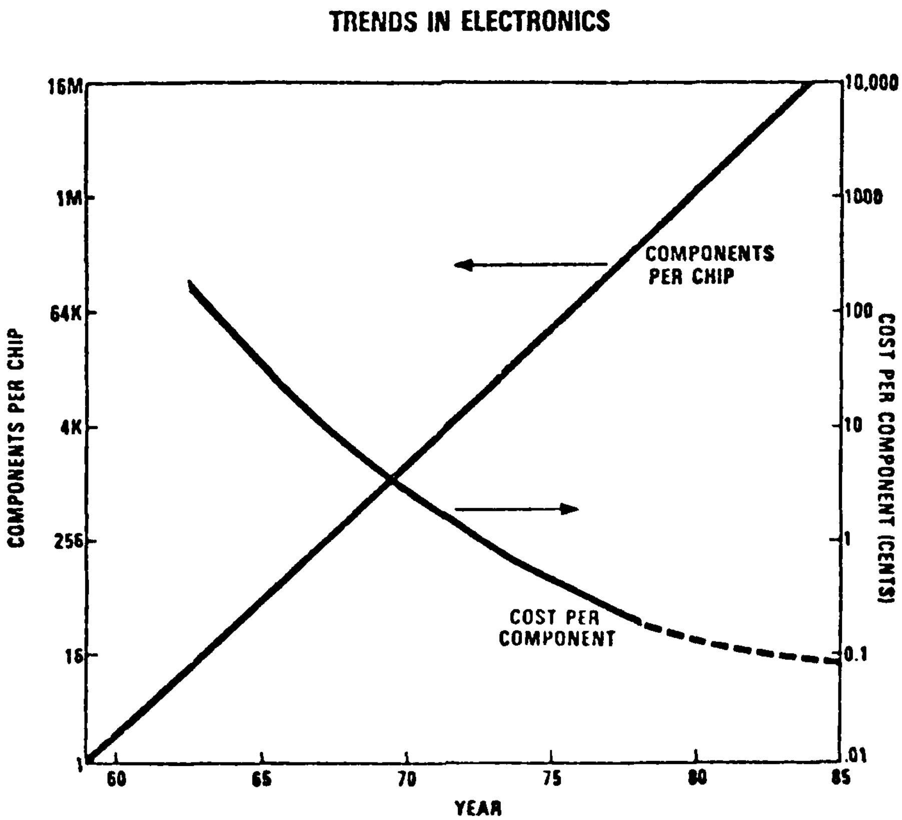


Figure 23

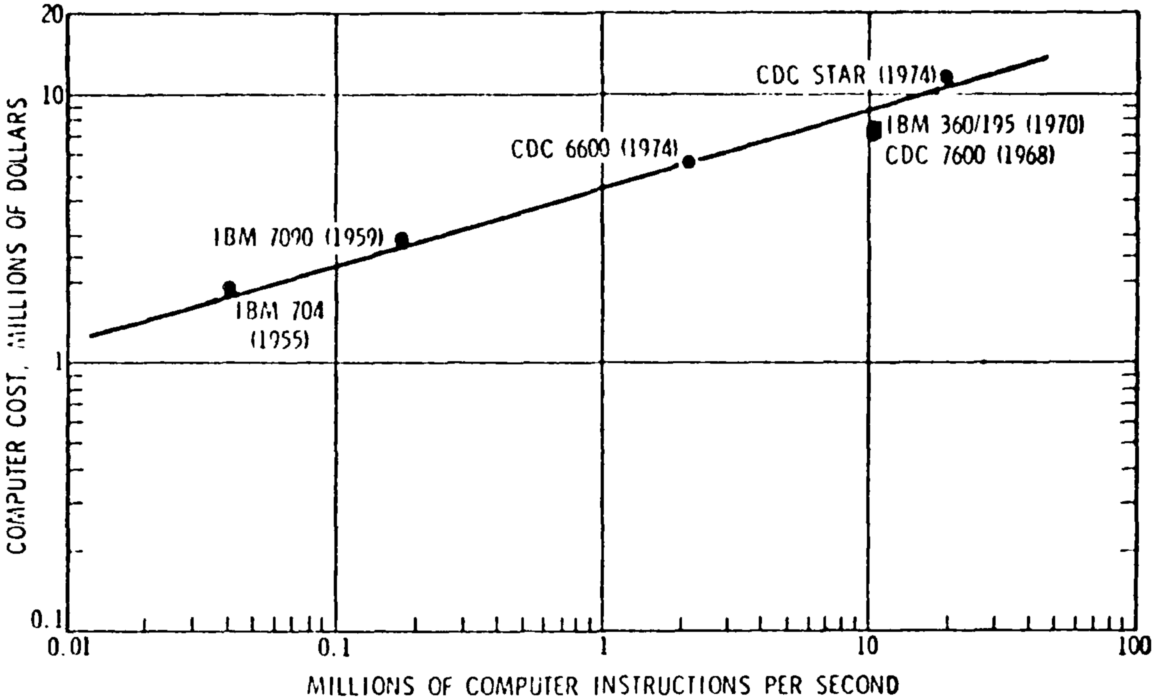


Fig.9 Computer cost as a function of capability and date of first delivery

Figure 24

STRATEGIES

- REDUCE NUMBER OF PARTS
- USE INHERENTLY RELIABLE COMPONENTS SOLID STATE - MSI, LSI
- REDUCE WASTE OF COSTLY MATERIAL
    - LAYUPS
    - CASTINGS AND FORGINGS CLOSE TO FINAL SHAPE
- REDUCE MACHINING TIME
    - FORGE CLOSE TO NET SHAPE
    - CAST TO NET SHAPE
- STANDARDIZATION OF ARCHITECTURE AND INTERFACE SPECIFICATIONS
- COMMON ELEMENTS / MODULE BUILDING BLOCKS
- STANDARDIZATION OF HARDWARE WITH FLEXIBILITY
- REDUCE SENSITIVITY TO PRECISE PROCESS CONTROL OR OPERATION USAGE
- REDUCE FABRICATION ENERGY REQUIREMENT
- EFFECTIVE NDE
- CORROSION AND CRACK RESISTANT MATERIALS

Figure 25

HIGHER ORDER SYSTEMS ANALYSIS

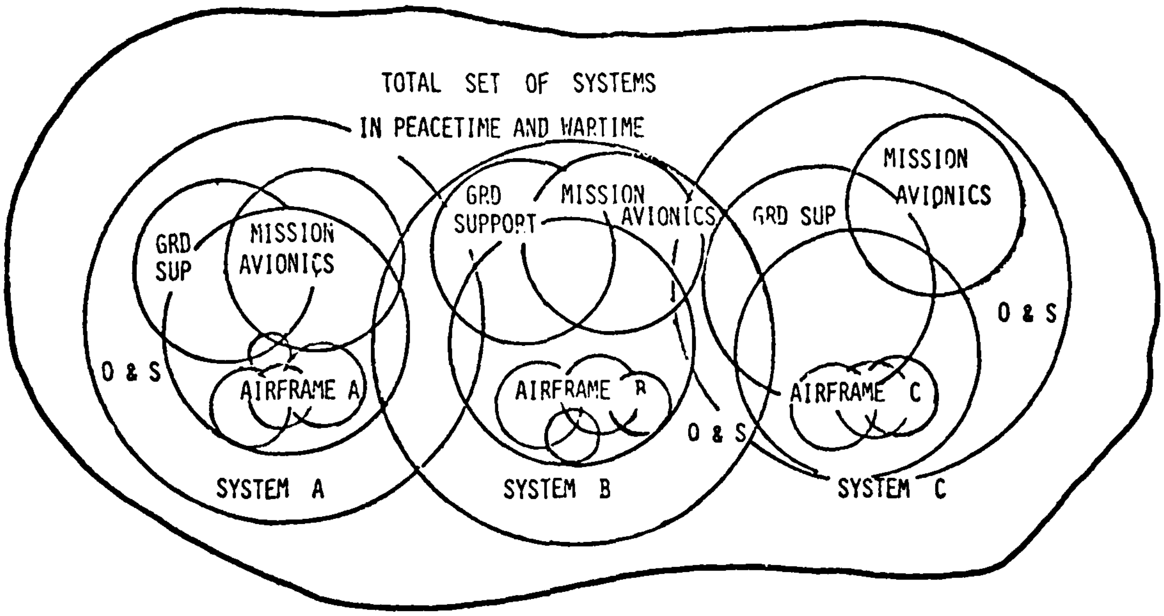


Figure 22

TRENDS IN ELECTRONICS

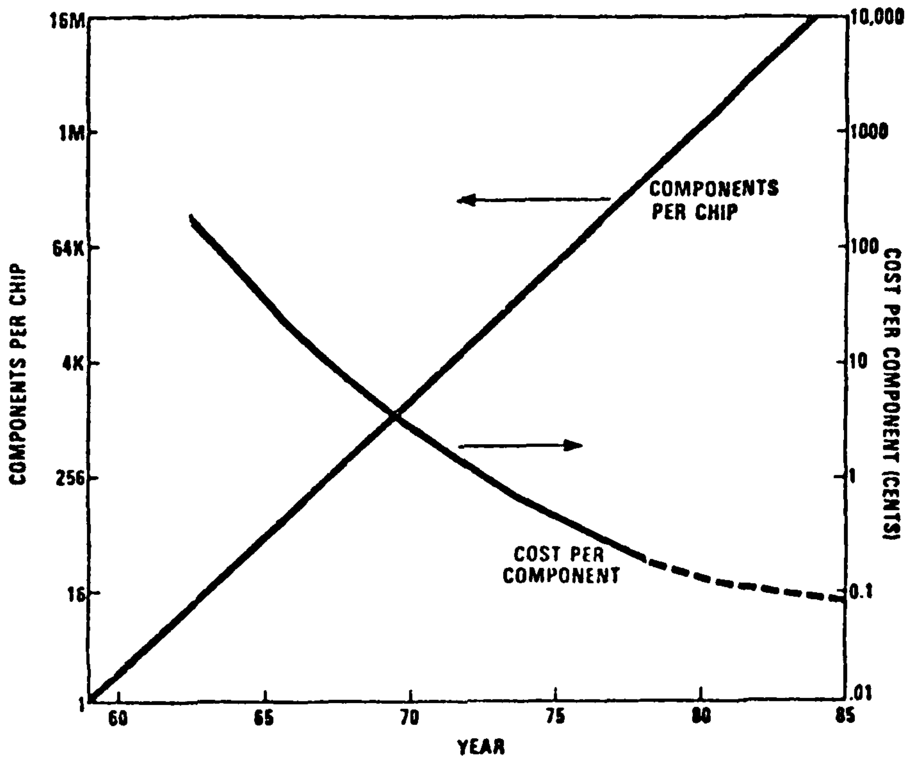


Figure 23

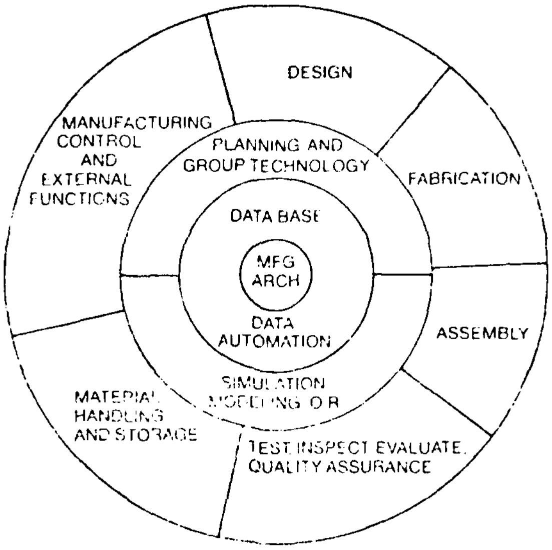


Figure 26

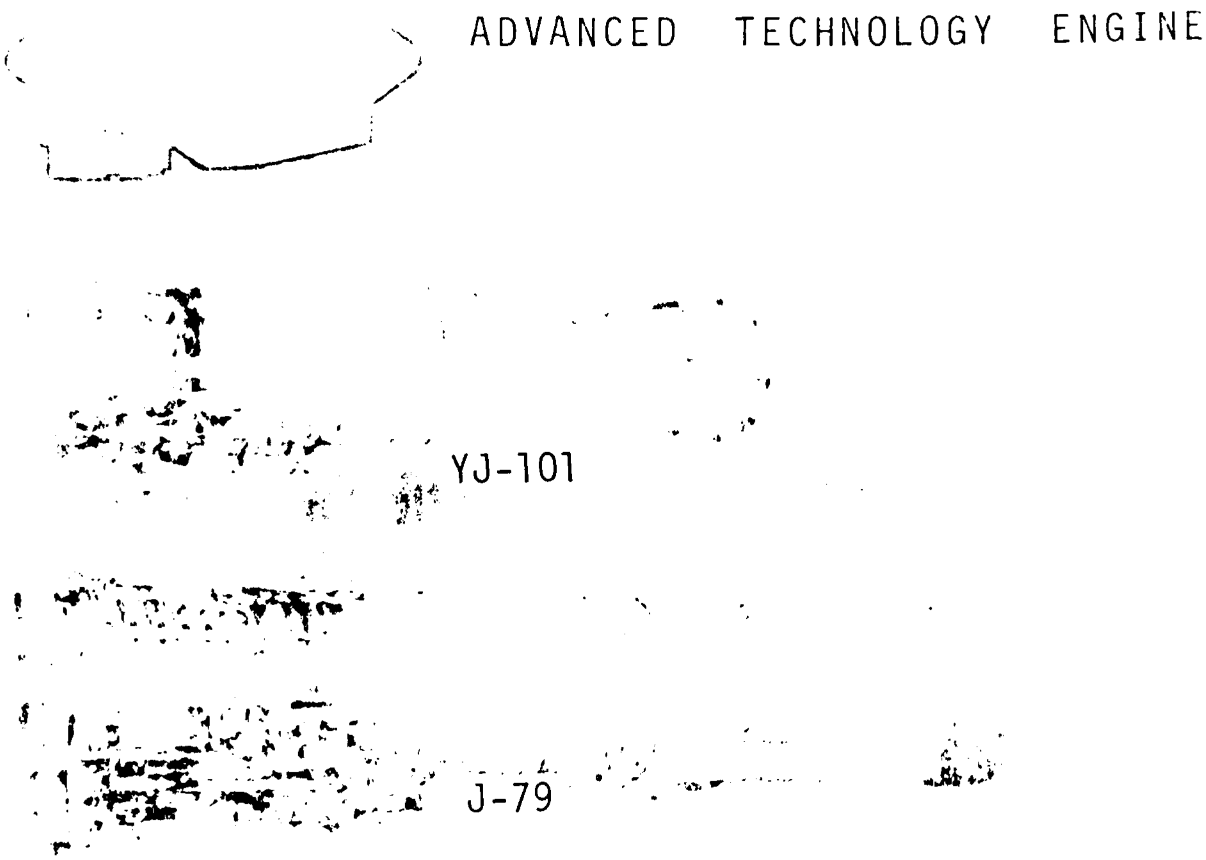


Figure 27

F-16 ADVANCED INTEGRATED TECHNOLOGIES

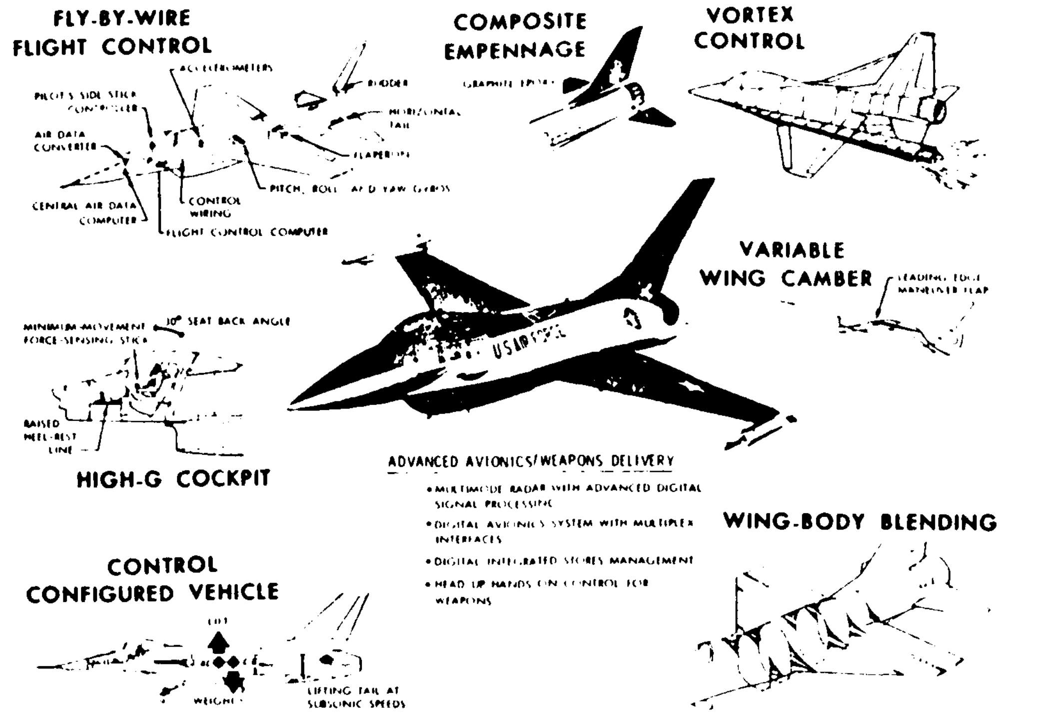


Figure 28

CARGO AIRCRAFT
TYPICAL MAINTENANCE BREAKDOWN

Maintenance man hour expenditures	Maintenance man-hours per flight hour	% of total
Direct system maintenance		
On equipment	9.25	32.26
Shop	3.19	11.13
Subtotal	12.44	43.39
Support general maintenance		
Inspections	4.65	16.21
Servicing	9.70	33.81
Other	1.66	5.79
Subtotal	16.01	55.79
TCTO	0.23	0.80
Total direct maintenance man hours per flight hour	28.68	100.00
Maintenance task frequencies	**Tasks per 1,000 flight hours**	**Maintenance man hour per task**
Flightline	3,636.4	2.54
Shop	854.3	3.74

Figure 29

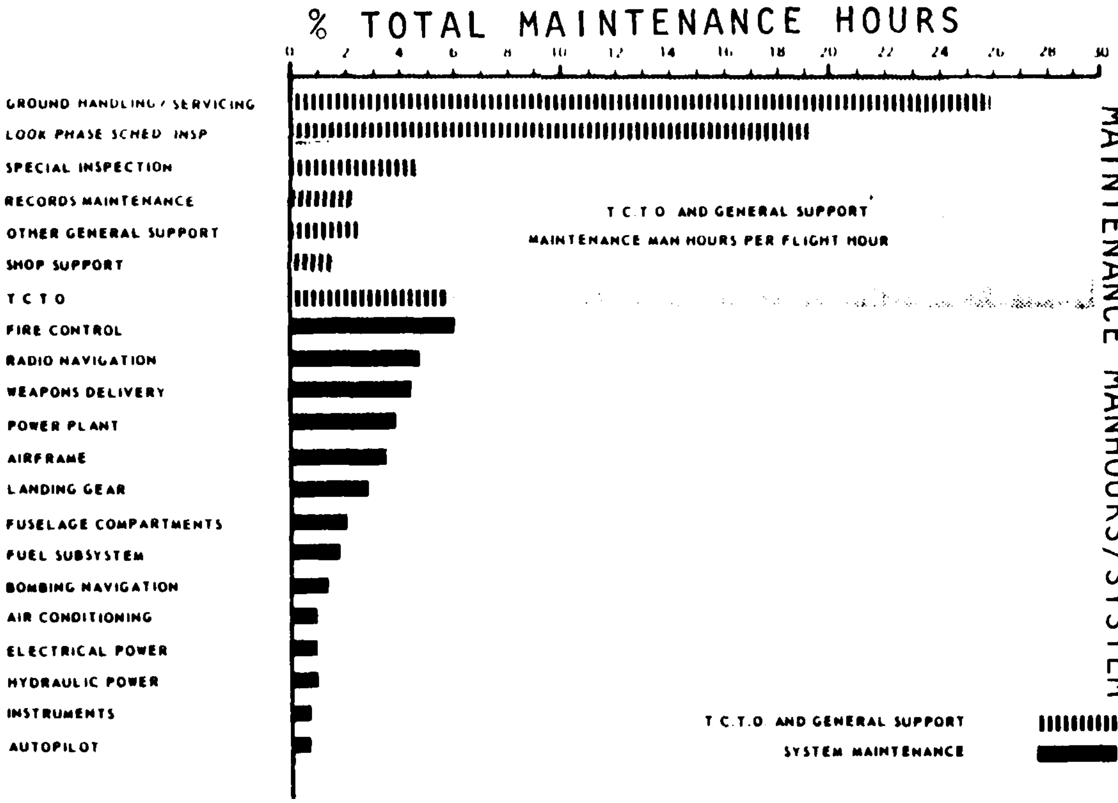
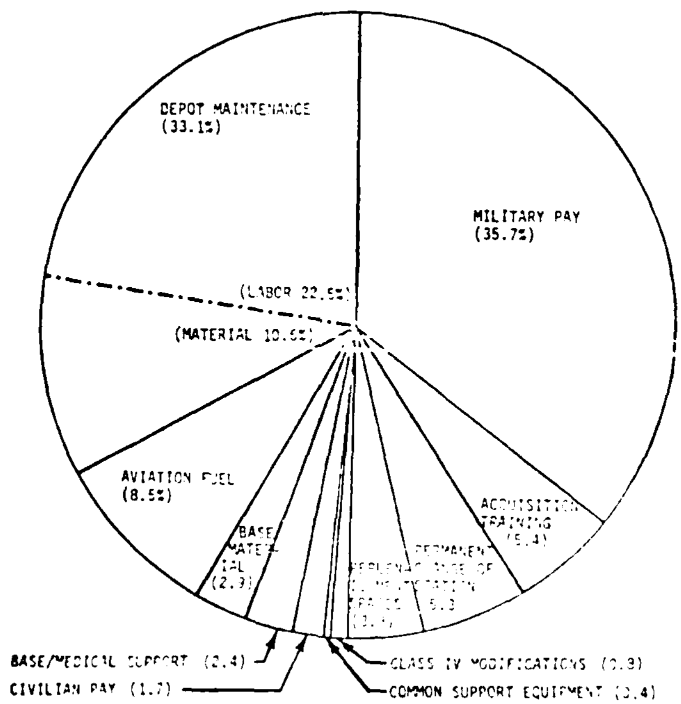


Figure 30



15 YEAR O&S COST BY MAJOR CATEGORY
CARGO AIRPLANE

Figure 31

LIFE CYCLE COST ANALYSIS WORKSHEET

DEVELOPMENT — TOTAL DEVELOPMENT COST = [ ] 00*

PROCUREMENT

- SYSTEM INVESTMENT = [ ] 01
- SUPPORT INVESTMENT
  - SUPPORT EQUIPMENT = [ ] 02
  - BASE SPARES = [ ] 35
    - QTY PER BASE = [ ] 36
  - DEPOT SPARES = [ ] 37
    - QTY = [ ] 38
  - 02 + 35 + 37 = [ ] 39
- TOTAL PROCUREMENT COST = [ ] 40

OWNERSHIP

- BASE MAINTENANCE MANHOUR = [ ] 41
  - DIRECT MANHOURS PER BASE PER YEAR = [ ] 42
  - PEAK MONTH DIRECT SHOP MANHOURS = [ ] 43
- BASE MAINTENANCE MATERIAL = [ ] 44
- DEPOT MAINTENANCE MANHOUR = [ ] 45
  - DIRECT MANHOURS PER YEAR = [ ] 46
- DEPOT MAINTENANCE MATERIAL = [ ] 47
- SECOND DESTINATION TRANSPORTATION = [ ] 48
- CONDEMNATION SPARES = [ ] 49
  - QTY FOR LIFE CYCLE = [ ] 50
- INVENTORY MANAGEMENT = [ ] 51

TOTAL OWNERSHIP COST = [illegible] = [ ] 52

LIFE CYCLE COST = 00 + [illegible] = [ ] [illegible]

NOTES:

The numbers located adjacent to the boxes indicate the storage/output location in the program.

Figure 32

AVIONICS DESIGNERS COST MANUAL -- VOL I

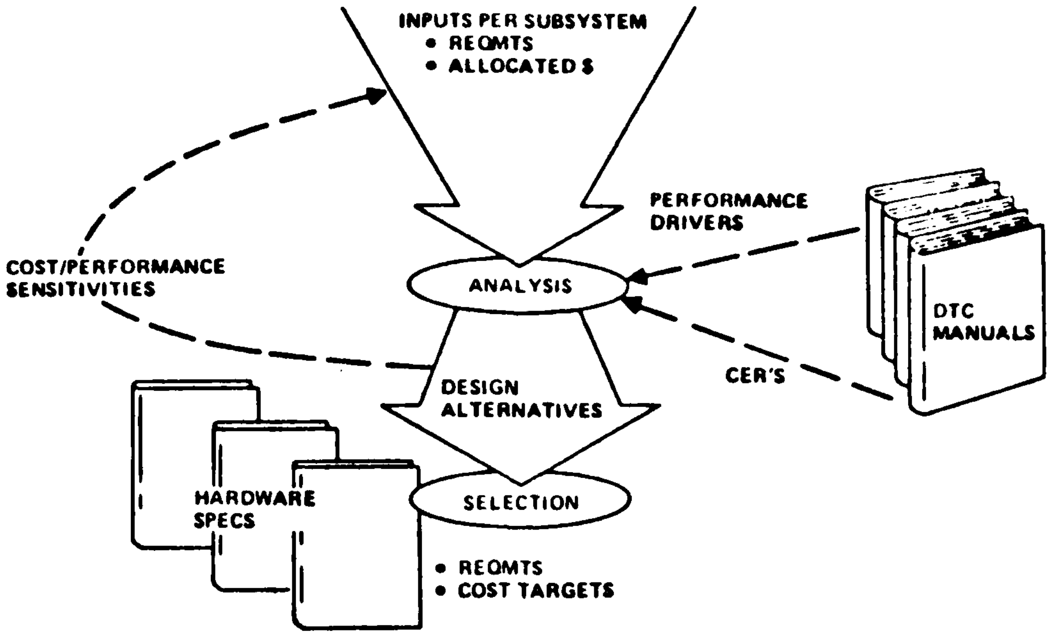


Figure 33A

EQUATION DEVELOPMENT MATRIX

SUBSYSTEM / COST ELEMENTS	STRUCTURE																			OTHER			
	WING	FUSELAGE	EMPENNAGE	WING NACELLE	RAW MATERIAL	TOTAL	CREW SYSTEM	LANDING GEAR	FLIGHT CONTROL	ENGINES	ENGINE INSTALLATION	APU	ECS	ELECTRICAL	HYDRAULIC/ PNEUMATIC	FUEL SYSTEM	AVIONICS	ARMAMENT	CARGO HANDLING	FINAL ASS'Y	SUST'G	Q.C	TOTAL
• RDT&E																							
– AIRFRAME																							
ENGINEERING																							•
TOOLING																							•
MANUFACTURING																							•
O D CHARGES																							•
- AVIONICS																	•						
- ENGINES										•													
• PRODUCTION																							
· AIRFRAME	•	•	•	•	•		•	•	•		•		•	•	•	•		x	⊗	•	•	•	
- AVIONICS																	o						
ENGINES										•													
• INITIAL SUPPORT																							
SPARES						•	•	•	•	•	•	⊗	•	•	•	•	•	•	⊗				
SUPPORT EQUIP						•	•	•	•	•		⊗	•	•	•	•	•	•	⊗				
CONTRACTED TRAIN'G																							x
DATA						•	•	•	•	•	•	⊗	•	•	•	•	•	•	⊗				
SPECIAL SUPPORT EQUIP																							x
• OPERATIONS & SUPPORT																							
BASE LEVEL MAINT						•	•	•	•		•	⊗	•	•	•	•	•	x	⊗				
BASE LEVEL TRAIN'G																							•
BASE LEVEL OPS PERS																							•
DEPOT AIRFRAME (POM)																							•
DEPOT COMPONENT REPAIR						⊗	•	•	•		•	⊗	•	•	•	•	•		⊗				
DEPOT ENGINE REPAIR										•													
REPLENISHMENT SPARES						•	•	•	•		•	⊗	•	•	•	•	•		⊗				
POL																							·
OTHER																							•

x SINGLE CER FOR FIGHTER/ATTACK A/C ONLY

⊗ SINGLE CER FOR CARGO/TRANSPORT/TANKER A/C ONLY

· SINGLE CER APPLICABLE TO FIGHTER/ATTACK & CARGO/TRANSPORT/TANKER AIRCRAFT

• TWO CER'S ONE FOR FIGHTER/ATTACK, ONE FOR CARGO/TRANSPORT/TANKER AIRCRAFT

· THREE CER'S ONE FOR FIGHTER, ONE FOR ATTACK AND ONE FOR CARGO/TRANSPORT/TANKER A/C

Figure 33B

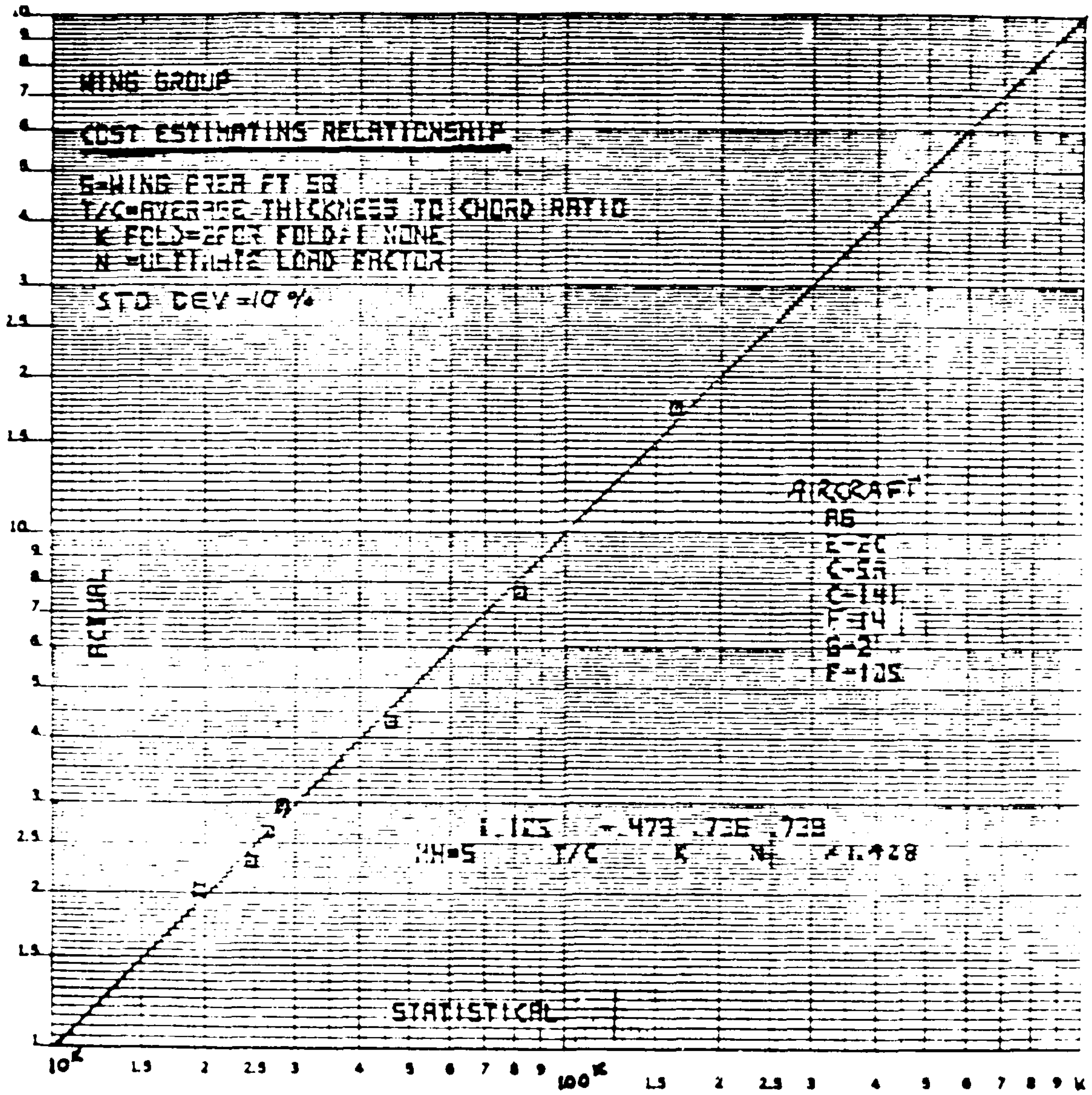

WING GROUP
COST ESTIMATING RELATIONSHIP
S=WING AREA FT SQ
T/C=AVERAGE THICKNESS TO CHORD RATIO
K FOLD=2 FOR FOLD/1 NONE
N =ULTIMATE LOAD FACTOR
STD DEV =10 %
AIRCRAFT
A6
E-2C
C-5A
C-141
F-14
G-2
F-105
ACTUAL
1.125 -.473 .736 .739
WH=S T/C K N ×1.428
STATISTICAL
10K
100K

Figure 34

DESIGN TO LIFE CYCLE COST RESEARCH

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SUMMARY

Design to life cycle cost research applied to the area of logistics systems is new. The approach starts with a look at history data for typical aircraft systems. Deficiencies in systems operations and support are identified and described. Methods of assessing the cost, risk and program application are discussed. Areas of emphasis, cost drivers and their impacts are shown. It is determined that many deficiencies in the ownership of systems do not relate to program plans. Resolution by future technology advances must be aimed toward elimination of manpower, materiel and program causative factors through research of logistics subsystems, i.e. inspections, materiel distribution, people use and logistics networks. Many technology opportunities developed through design to life cycle cost research will be of great benefit to all allied countries.

Life cycle cost studies conducted over the past five years have confirmed a need to perform research on the life cycle cost of systems. Because most of my background is in logistics support of systems, I will use as my research example, operations and support. Of all the stages of the system life cycle, operations and support (sometimes called ownership) receives the least attention by people working on the support environment until system design has reached a point that fixes support to old concepts. This lack of emphasis on the technology of support has resulted in high ownership costs and systems not being ready to perform their mission.

Before going on, we should establish certain definitions and objectives. The life cycle definition is shown on Figure 1. Very often, development and production together are called acquisition and ownership is called operations and support. Sometimes, ownership includes disposal. To me, design to life cycle cost includes all of those tasks listed on Figure 1. One man cannot do all of those tasks--so we are talking about a team, i.e. designer, producer, logistician, cost estimator and manager, at the least. But, what about the technologist who devises better schemes for systems which can perform, be ready, and do the job at less cost for the life cycle? He must include life cycle cost in his research to accomplish the objective shown as the last item on the chart.

- **LIFE CYCLE = DEVELOPMENT + PRODUCTION + OWNERSHIP**

- **DESIGN TO LIFE CYCLE COST**

  ASSESS HISTORY
  IDENTIFY DEFICIENCIES
  DEFINE ALTERNATIVE SOLUTIONS
  SELECT SYSTEM/SET GOALS
  DESIGN PROGRAM TO GOALS
    SCENARIO
    STRATEGY
    HARDWARE
    SOFTWARE
    PROGRAM METHODS

- **LIFE CYCLE COST RESEARCH - IMPROVE AND REDUCE THE DEVELOPMENT, PRODUCTION AND DEPLOYMENT, OPERATIONS AND SUPPORT OF SYSTEMS AND EQUIPMENT**

Figure 1. Definitions and Objectives

The first two tasks under design to life cycle cost are the assessment of history and the identification of deficiencies. So, let's take a look at history. A look that not only considers hardware history, but support concepts history as well. I could spend several hours discussing the differences and how they impact the life cycle of systems. Instead, I will use a few examples to delineate the deficiencies and problems which technology needs to solve. Some of those deficiencies cannot be solved during the normal acquisition process. They need separate attention for awhile--just as we give separate attention to aircraft engine development, or flight control development.

All of the support deficiencies are not found by analyzing the hardware data base, Figure 2. Some are in ground equipment, support people, control points and the interfaces among hardware and support. Through good design of the system and its crew application, we achieve medium to high readiness. For example, we can remove and replace the communication equipment within the time limits and the crew has been taught to recognize failure or degradation so they can brief the maintenance personnel. Then the removed part goes back through the supply system. The delivery and distribution system breaks down so that long delays are incurred and added stockage of materiel results in high cost.

The solution--do we pour more resources into the breach or ask technology to help us? The long term solution is through a technology change. We do not find this kind of deficiency in our data files and there is no real testing of this support condition during acquisition. Can it be tested? Certainly it can; however, the early test prototype must be more like the production and operating unit. It is too late to test without added cost, if we wait until detailed design is in progress.

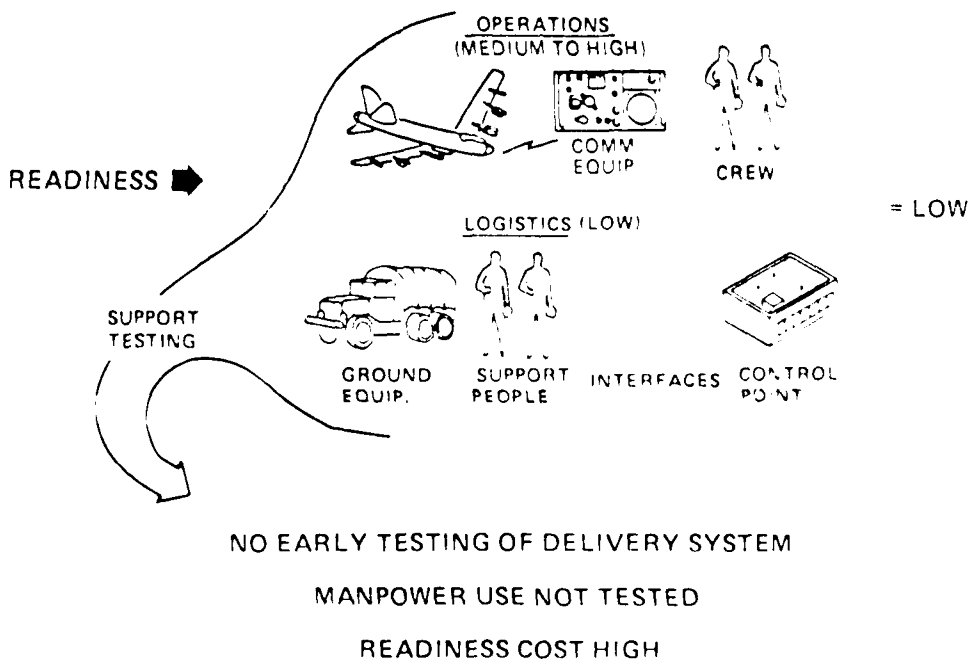


Figure 2. Support Deficiencies

The history base also tells us that we must tailor our emphasis on cost to the program and its cost areas which have the most potential savings, Figure 3. We must analyze the high value areas. Over 20 to 30 years of system life, the main bulk of money is spent to support systems in peacetime. Typical system expenditures are shown under some continuing budget line. In one case, a few unmanned aircraft are acquired and supported for a life cycle cost factor of 1. A different quantity of stored missiles are obtained for a factor of 2--and so on to a high operating time system, e.g. aircraft, for a factor of 20. The functions of acquisition and support, shown on the right, must be questioned to find the cost drivers. If the concepts of operations and support are fixed too early in the program, i.e. before support trade-off, the beneficial cost reduction may be reduced to less than 5 percent.

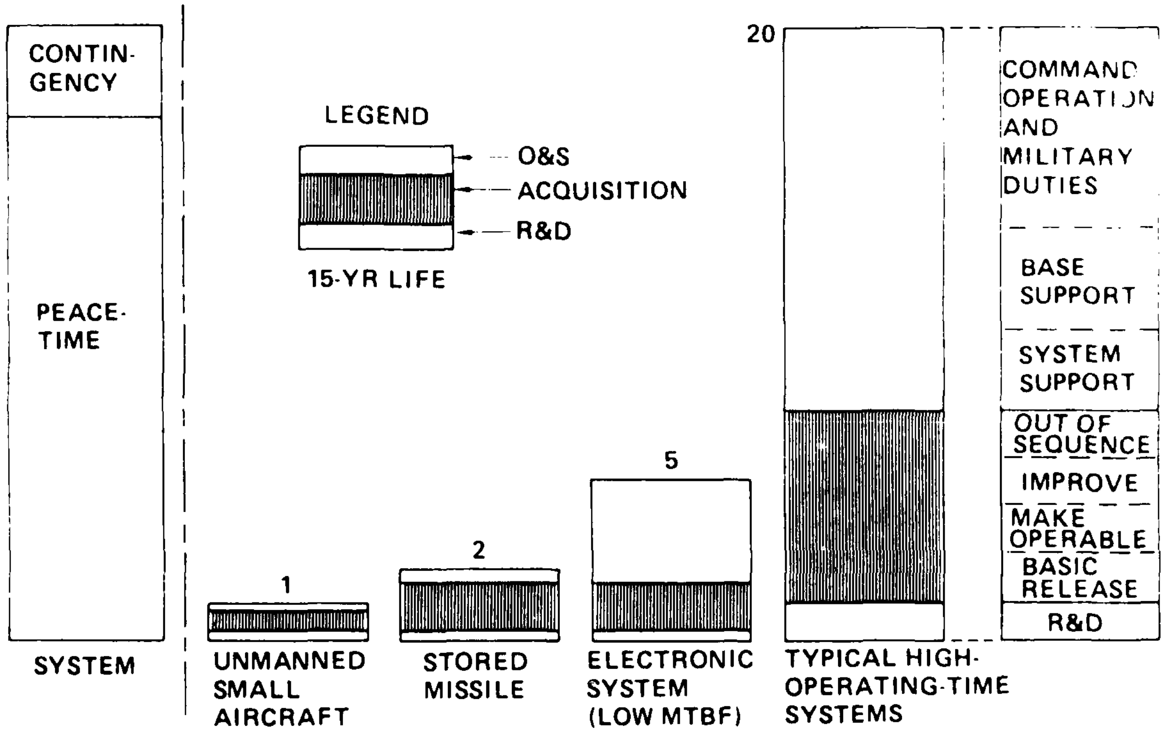


Figure 3. High Value Areas

Let us use, as another example, the trends for reliability on contemporary systems. A recent issue of the U.S. Defense Management Journal included the information shown in Figure 4. The difference between specified, predicted or demonstrated, and actual field values varied as much as 60 to 1. If the reliability figures were used in support resource planning, there would generally be initial shortages of resources. Additional shortages due to lack of funds made logistics support planning almost useless.

One of the major issues relates to the severity of laboratory and demonstration tests versus field use. In some recent cases, the enviromental tests were so severe that the mean-time-between-failure pattern for resource planning could have been reversed from that shown on the chart. Research on the inspection and test of field resources needs to be accomplished to close the gap between the work package design team and the user, i.e. make predicted values more closely relate to field achieved reliability.

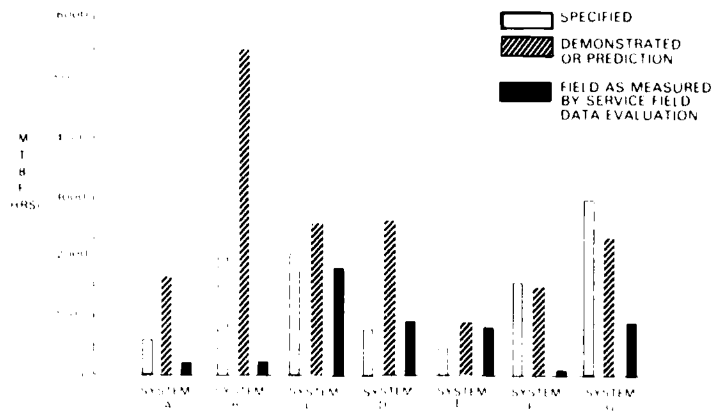


Figure 4. Selected Equipment Reliability Trend for Contemporary Weapon System

Are all the failures of the system inherent to the hardware? No. Figure 5 shows that on the average, human induced failures are about five times those inherent in the hardware. Human induced failures are those which, for example, result from improper operating procedures, gaining access by removal of nonrelated structure and equipment, and excessive testing or hands-on activity during pre and post-operations.

Does this data show up in the collection system? It does not. The only way to gather it now is by eyeball-to-eyeball interrogation of the user. So, if you tell me you do not have this problem, I would certainly like to see your data system. How can we do a proper job of researching and designing systems, when 60 to 80 percent of the data is missing?

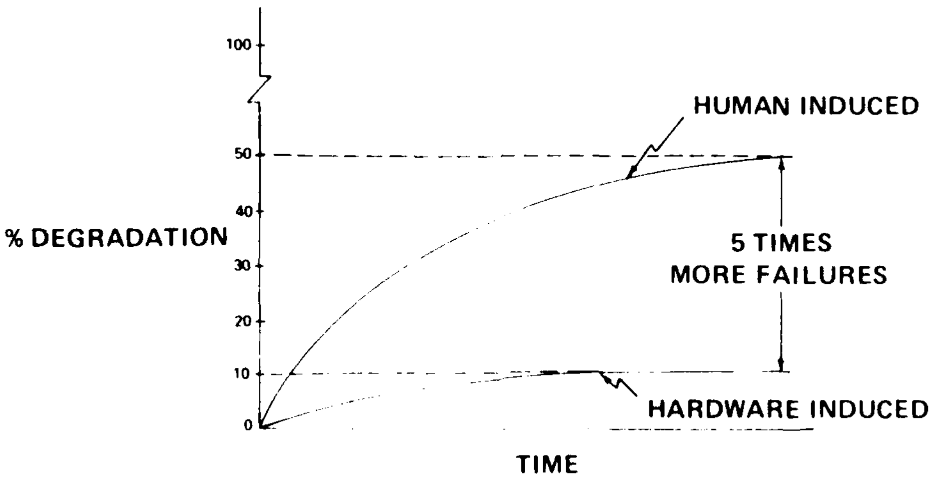


Figure 5. Systems Degradation by Type (Results of 5 Programs

The collection of data for aircraft from the operating bases shows high cost areas in terms of maintenance manhour expenditures, Figure 6. The areas of emphasis may be selected as those falling into the general support maintenance, i.e. the three top bars on the chart. Also, there are three or four areas of system hardware maintenance that need attention. We now have data, not shown on the chart, that identifies the cost drivers within each bar. We need to draw attention to solving those drivers by hardware and logistics technology, and by program actions early in mission analysis and concept development.

In the past, there has been no difference in the specifications for the short bars on hardware versus the long bars on both hardware and support. All receive equal treatment in achieving performance of the aircraft. We should know in advance that 10 or 12 items on past similar systems contribute 70% of the base maintenance, 74% of the depot repair actions, and 89% of the spare parts cost. Now, the 10 or 12 items are not the same for each case. We should know in advance what they are! Otherwise, our development teams will concept and include the same high cost and/or low readiness drivers in their new design.

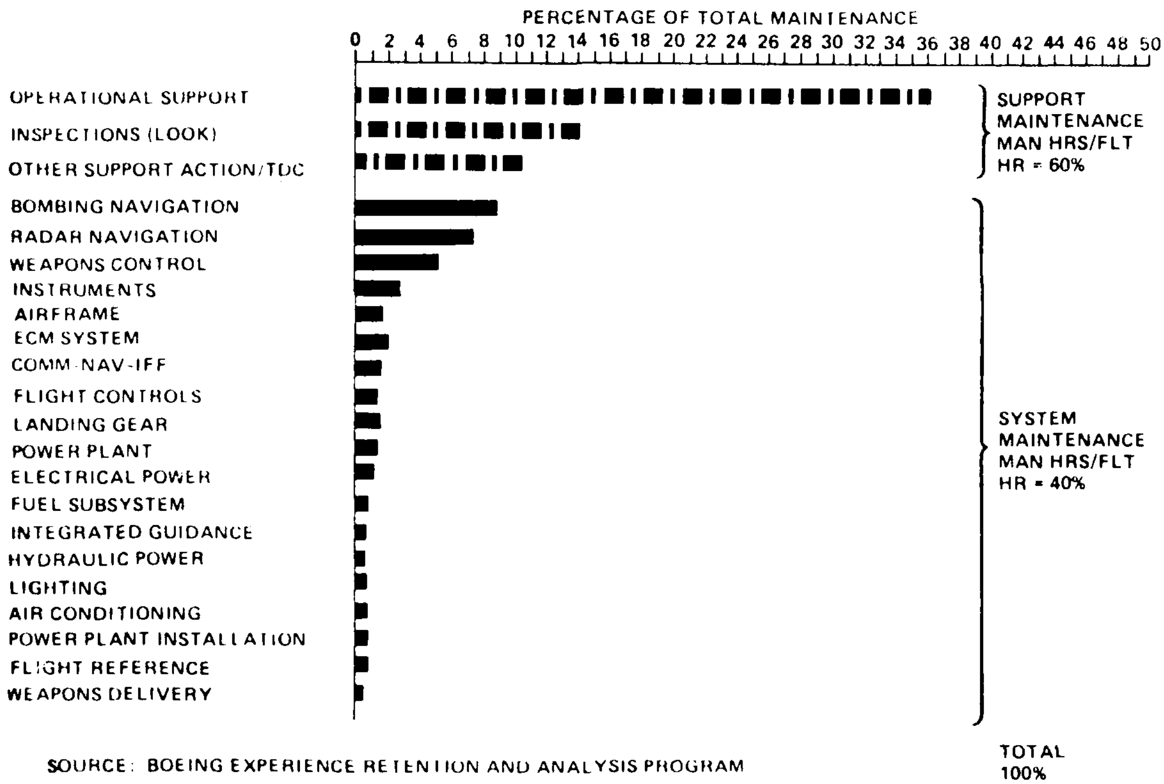


Figure 6. Areas of Emphasis

The areas of emphasis are the same for different categories of aircraft, Figure 7, we may call them concept cost drivers if the data has been researched enough to know what factors are causing the high maintenance manhours. There are a few differences in the system maintenance area because of the scenario for cargo versus bomber and fighter aircraft.

The data shows that we in technology should be working now on eliminating ground handling and servicing, scheduled inspections, and maintenance problems associated with bomb navigation transmitters and cargo aircraft landing gear. A note of caution is in order. Examine the complete life cycle thread from factory through operations. The cost drivers may change somewhat and other areas of emphasis may be added. Also, the reason we advocate a team effort in technology and early acquisition is that cost is not the only function that we should research for the 10 or 12 drivers. Mission, performance, readiness, and timing should be included.

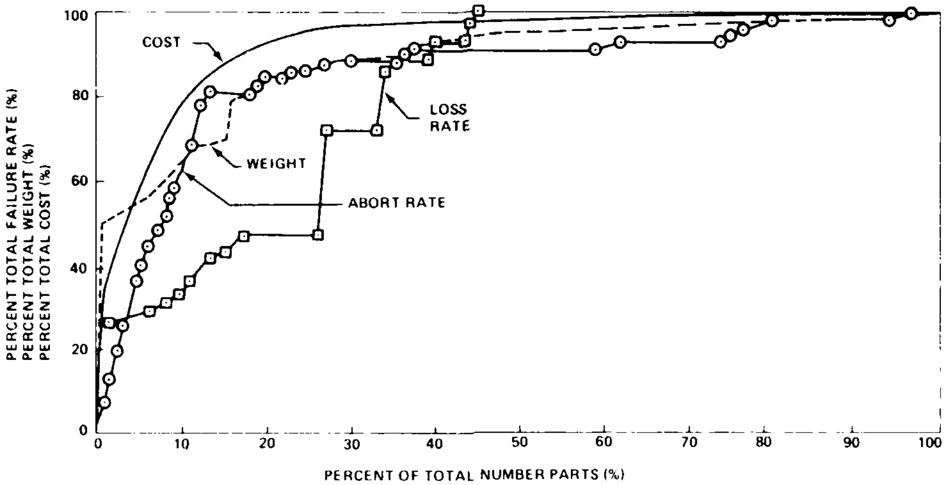
Also, should the team research the cost drivers as part of a system program, or do it as a separate support program to correct the problem on all categories of aircraft? In the latter case, resultant solutions may then be applied to on-going programs.

	BOMBER	CARGO	FIGHTER
GENERAL SUPPORT	61%	52%	62%
GROUND HANDLING & SERVICING	36	20	26
SCHEDULED INSPECTION	14	13	19
OTHER GENERAL SUPPORT	4	6	3
TCTO	3	5	6
SPECIAL INSPECTION	2	4	5
AIRCRAFT CLEANING	1	2	2
SHOP SUPPORT	1	2	1
SYSTEM MAINTENANCE	39	48	38
BOMB NAVIGATION	9		7
RADAR NAVIGATION	8	4	5 (RADIO NAV)
WEAPONS CONTROL	6		6 (FIRE CONTROL)
INSTRUMENTS	3	2	1
AIRFRAME	2	8	6
ECM	2		
COMMNAV - IFF	2		
FLIGHT CONTROLS	1	4	
LANDING GEAR	1	10	3
POWER PLANT	1	9	4
ELECTRIC POWER	1	2	1
FUEL SYSTEM	.5	2	2
GUIDANCE	.5	1	1
HYDRAULIC POWER	.5	3	1
LIGHTING	.5	1	
AIR CONDITIONING	.5	1	.5
WEAPONS DELIVERY	.5	1 (AUX POWER)	
OTHER		1	.5

Figure 7. Concept Cost Drivers

For another example, a small number of purchased equipment parts contribute 90% of the cost for a particular aircraft, Figure 8. Also, a small number of parts contribute to most of the weight, loss rate, abort rate and many other problems. We should have guidance on the direction to take on evolving solutions to these cost and other drivers before we complete mission analysis and start concepting a new system.

You may answer, "How can I do that? I do not yet know the details of my concept or system." My answer to you is, "You have a history base full of information--perhaps not in a well-constructed file--but in the heads of old maintenance and supply people like me, who can tell you in a few minutes what the big drivers are." But, you also have to ask the right questions--just as you do when you interrogate structures and other project personnel on weight problems.



17% OF P.E. PARTS CONTRIBUTE 90% OF COST

Figure 8. Purchased Equipment Drivers

The cost of reliability varies with the amount of screening and testing needed to assure achievement, in the field, of the predicted performance and readiness, Figure 9. It is not important to know the test and screen requirements on the chart. It is important to question the program cost when it rises by an order of magnitude for a nonpriority item that did not need testing and screening. In some cases, the item did not have a connection to the real life deficiencies. Its inherent reliability was high. It was low on the list of priorities. Sometimes, its field reliability was low because it was removed often to reach another failed item. The primary causes of low reliability were bad packaging and human induced failures.

Unless all of the causative factors are included in the data package for the early phases of the next program, much time will be erroneously spent in the research and design of a better hardware unit. This example is only one of many where there is a mismatch between ownership deficiencies and the normal "success path" planning done by systems, production and logistics engineers.

DERIVATIVE PROGRAM HTL INTEGRATED CIRCUIT—NUMBER REQUIRED 100

REQUIREMENT	MINIMUM QTY	PRICE
• STANDARD COMMERCIAL	100	$ 498
• 100% SCREENED PER MIL-STD-883	100	$1480
• SCREENING PLUS GROUP B TESTING PER K-883	1241 (1)	$5925
• SCREENING PLUS GROUP B&C TESTING PER -883	1372 (1)	$8410

(1) 1000 MINIMUM BUY PLUS TEST SAMPLES

Figure 9. Cost of Reliability

The real life logistics picture (situation) shows very little matchup between the program plans success path and the ownership deficiencies experienced on systems as they are operated in field conditions, Figure 10. What do the words "success path" mean? They mean that our technologists and engineers have chosen a concept and design such as a navigation system transmitter that will be removed and replaced, sent to a depot, repaired or rebuilt and returned to inventory, just as has been done for the past decade. Once the hardware has been selected or designed, and the concept of maintenance accepted, the life cycle cost is fixed to the materiel needed, the people in the cycle, and the pipeline times dedicated to surrounding infrastructure. Deficiencies such as those shown in the right column are prevalent in the field. Their solutions cannot be found in the success path plans.

Current technology does not now, but must in the future, include the research and development of means to reduce or eliminate the ownership deficiencies. The formal data system must show what the causative factors are. There is much data in the heads of individuals who have had to cope with field problems. We, as technologists, must learn how to ask the right questions. When asking the questions of the operators and support personnel, we must ask ourselves, "Can I solve these deficiencies as part of system and hardware programs, or do I need to research them separately to arrive at logistics solutions--hardware and/or procedural?"

SUCCESS PATH PLAN ⟷ NO CURRENT MATCHUP ⟷ **OWNERSHIP DEFICIENCIES**

SUCCESS PATH PLAN

SYSTEM & EQUIPMENT REQUIREMENTS FOR:
- MAINTENANCE
- FACILITIES
- SUPPORT EQUIPMENT
- PERSONNEL
- TRAINING
- PUBLICATIONS
- LOGISTICS MANAGEMENT

DESIGN CHARACTERISTICS BASED ON ABOVE:
- MAINTAINABILITY
- RELIABILITY
- AVAILABILITY
- SUPPORTABILITY
- . . . . . .
- . . . . . . ILITIES

OWNERSHIP DEFICIENCIES

PERSONNEL CAPABILITY
- TECHNOLOGY MISMATCH
- TRAINING LIMITATIONS
- TENURE ON JOB
- EQUIPMENT AGING
- CONTINGENCY READINESS

MATERIEL DISTRIBUTION
- READINESS
- MANPOWER COST
- RESOURCE ORIENTATION
- EXCESSES AND LOSSES
- ASSETS FRAGMENTATION
- COMMUNICATIONS

INSPECTION SYSTEMS
- DUPLICATION
- QUALIFICATION
- STABILITY
- MANPOWER COST
- WEAR
- TIME CREDIBILITY

Figure 10. Real Life Logistics Picture

History data shows the high cost areas in an aircraft system are those shown on Figure 11. For other systems they may be the same or different items. The high cost drivers are those causative things which exist because of unique applications, locations and concepts. Some people relate these driver characteristics to peculiar versus common (standard) parts. Sometimes you can have many common parts which are unique in application and location. Cost of acquisition and support can still be high.

When we relate the history data on hardware to the activities and locations in the use sequence, i.e. factory through operations, we find that people and materiel are not always used in a timely and economical manner. This means that the technology of systems has not been viewed in the light of use activities. Also, it means that the design did not include the total system factors, but dealt primarily with the hardware ability to perform an operating function.

HIGH COST AREAS ARE:

MANPOWER
DEPOT MATERIEL
TRANSPORTATION/DISTRIBUTION
BOMB NAV/PROPULSION/LANDING GEAR

HIGH COST DRIVERS ARE:

NUMBERS OF UNIQUE SYSTEMS
NUMBERS OF UNIQUE SKILLS
LOCATION OF FACILITIES
INSPECTION AND TEST CONCEPTS
MATERIEL DISTRIBUTION CONCEPTS

THE PROBLEM IS "PEOPLE AND MATERIEL ARE NOT USED IN A TIMELY AND ECONOMIC MANNER"

Figure 11. History Data Shows

How are people and materiel not used properly? The search for answers to that question involves the flow and magnitude of resources, Figure 12. For a missile system, the flow may be factory through launch. An aircraft system may involve development test through basing within the continental United States. A new tactical missile system may involve prototype test through theatre mobility. Whatever the flow sequence, the individual activities must be well understood. Knowledge of the people and materiel dollars for each activity must be gained. Activity factors which cause people and materiel to be high are drivers and must be redesigned and/or concepted.

New designs which only contemplate hardware operations, and their attendant trade-offs and savings, will pass through the support activity sequence, become part of each facilities pro-rated load and the savings from hardware design will be small. A significant concept change to the activity sequence will usually show greater benefits.

So, we have come to the point where you may ask, "How?" Let's spend a few minutes on an example approach to the research of a potential deficiency. Inherent in the approach is a good understanding of the mission and past history base, as well as the program activities which must decide the need, concepts, requirements, risks and demonstrations.

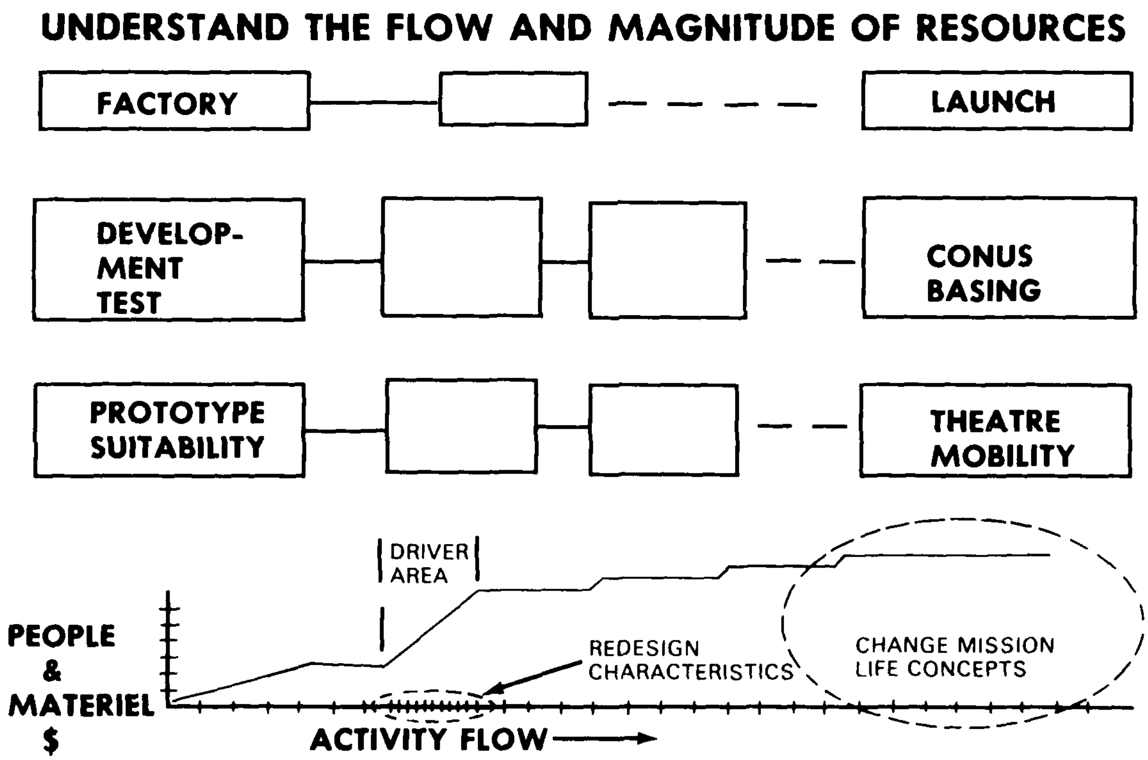


Figure 12. How are People and Materiel Not Used Properly?

Sometimes, a mission operations and support model helps in the understanding of the life cycle events of a system. In the past its use has been optional. In the future, our government, through the Office of Management and Budget Circular A-109 on the acquisition of systems, requires a mission, technology, operations and support analysis depicted by the model shown on Figure 13.

The model is based on a mission need. The need is stated in terms of a capability to solve a deficiency in operations. It must also include the logistics considerations for solving deficiencies in manpower, logistics requirements and readiness of resources. Then, a trade-off occurs between current systems, operations, support, and supply elements versus the optimum networks and designs which, when combined and compromised, lead to new designs for operations, support and supply bases as well as the programs. System redundancy, peak and normal operations for the life cycle must all be considered in setting the goals and thresholds for the new system.

If the model is initially restricted to high emphasis areas, cost drivers and potential risk factors, it will be manageable and can easily be done manually. As the program progresses to a model full of life cycle cost factors, it should be computerized. Today, I see too many life cycle cost models using too much unnecessary data too early. Technology should be mostly interested in the large benefits to be gained by design and concept changes which eliminate operations and support resources.

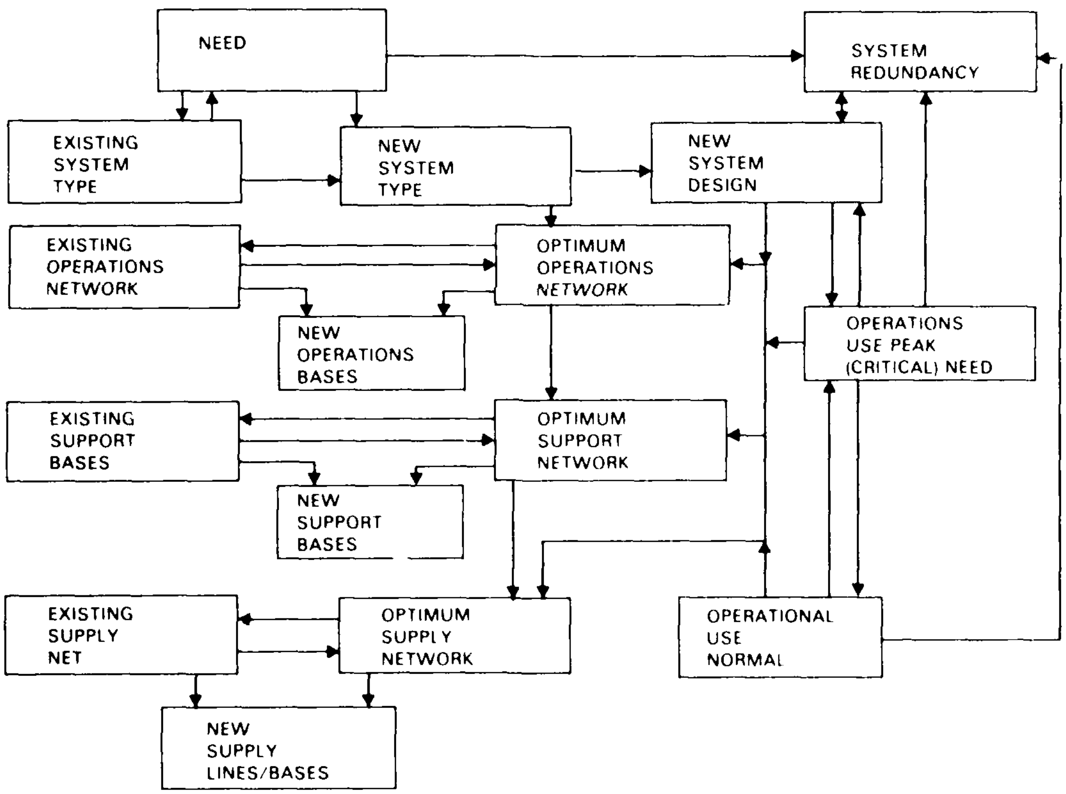
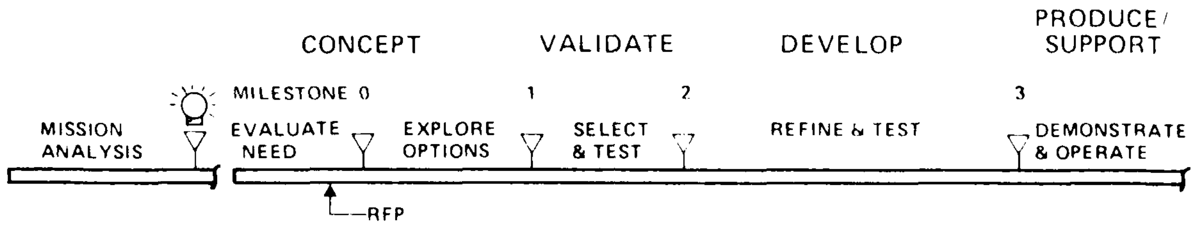


Figure 13. A Mission Operation and Support Model

If research precedes or is done concurrently with programs, it must be accompanied by an understanding of the program events, Figure 14, and how they relate to analyzing the deficiencies, evaluating the need, exploring optional solutions, selecting and testing the system, refinement and further test, and the production, deployment, demonstration and support of hardware. Milestone zero, one, two, and three are the program decision points to further proceed with system acquisition. In the future, one request for proposal (RFP) may suffice. The decision points may be extensions of the same contract(s). The elements under "mission analysis" all lead to the setting of program and concept strategy. The elements under "evaluate need" and "explore options" lead to the selection of the best system, elimination of risks, an optimum cost with maximum readiness, and the initial plans for carrying out the program. The elements under "select and test" establish the baseline system for refinement, the reliability, maintainability, and effectiveness goals, the procurement approach and a preliminary means of demonstrating the system. Logistics support analysis and rationalization--standardization--interoperability criteria for foreign planning furnish the data and specification input for follow-on design of support.

The logistics deficiencies must be exposed and the support subsystem solutions for inspections, materiel distribution and personnel use must be handled in the same manner as the hardware acquisitions. If you were developing engine technology and had an engine not yet ready to be included in the acquisition of a new airplane, you would separate that engine development from the program and run it concurrently as a special program until a decision could be made to include it with, or exclude it from, the aircraft system program. Logistics subsystem technology should be handled in the same manner. Let's take a quick look at how we might research and develop a better inspection subsystem for aircraft.



HISTORIES
DEFICIENCIES
PROBLEMS
RESEARCH
FIXED RESOURCES
STRATEGY
INTERNATIONAL
OBJECTIVES
AFFORDABILITY
ANALYSES

DESIGN TO O&S ANAL.
SCENARIOS
READINESS
CONCEPTS
FLOWS
DRIVERS
LOGISTICS &
R&M PARAMETERS
PRELIM. LCC GOALS
LOG RISKS
ILS TRADEOFFS
ILS PLAN
RESPONSIBILITY
STRATEGY
RSI
PREDICTIONS

ILS BASELINE
SCENARIO
READINESS
TEST & EVAL
REQMTS
PLANS
R&M & EFFECTIVENESS
DEMONSTRATION
PLAN
PROCUREMENT
STRATEGY
LOG. SUPP. ANAL.
RSI PLAN

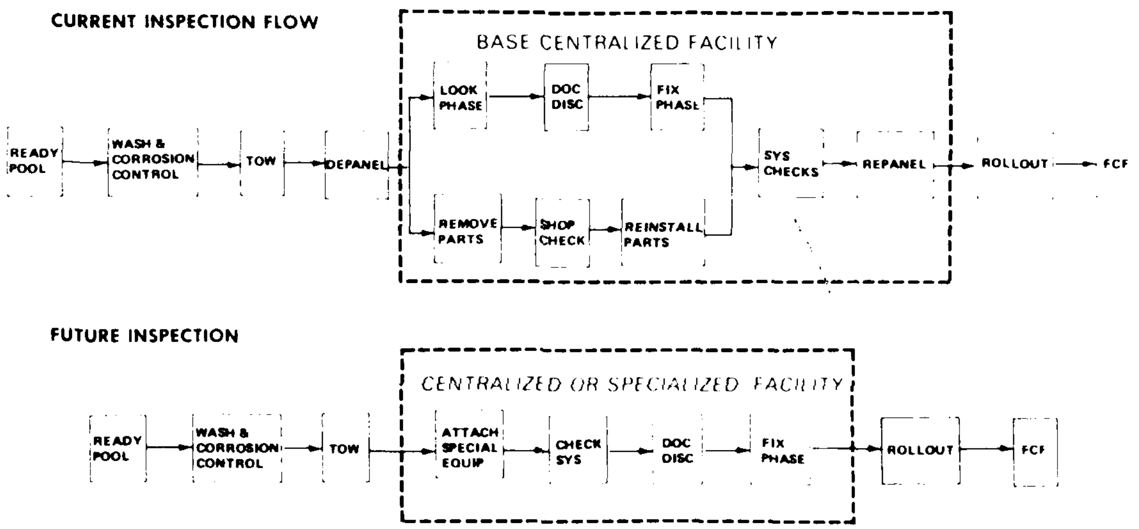
→

DETAIL
REFINE
TEST
EVALUATE
PROCURE
BUILD
OPERATE
SUPPORT
DEMONSTRATE

Figure 14. Programs Major Tasks and Milestones

To derive the deficiencies and their causes, we must understand the inspection flow for current support of aircraft, Figure 15. Then, we must identify potential solutions by functionally changing major events and detailed activities that are responsible for people involvement, equipment disturbance, excessive validation proofing, prolonged duration of inspections, and costly use of manpower. Data not available in current files must be obtained by direct discussions with using personnel.

The identified deficiencies must be separated into those which may require hardware technology versus those requiring procedural change.



- INVOLVEMENT
- DISTURBANCE
- EXCESSIVE VALIDATION
- TIMING AND DURATION
- TASK DEDICATED MANPOWER

Figure 15. Discovering Deficiencies and Causes for Inspection Subsystems

The identified deficiencies can be expressed as problems shown on Figure 16. Based on previous charts on reliability and human factors effects, we could sum up the solution as, "Develop the technology to remove the human from the inspection loop." Many alternatives may be available.

If the inspections were to verify the condition of a hydraulic actuator, Figure 17, we might reduce the manpower and cut wear and tear by doing the inspection with some kind of built-in or bench type acoustical test. If technology can determine means to significantly reduce the inspection manpower, what kind of application research can we do to effectively benefit current and future programs?

PROBLEMS

DUPLICATION OF INSPECTION EFFORT

MANPOWER QUANTITY & DEDICATION

QUALIFICATION REQUIREMENTS

WEAR AND DAMAGE

ALTERNATIVES

CATEGORY STANDARDIZATION

CONSOLIDATION OF LOCATIONS & EFFORTS

TECHNOLOGY TO VALIDATE CONDITION

Figure 16. Improved Inspection System

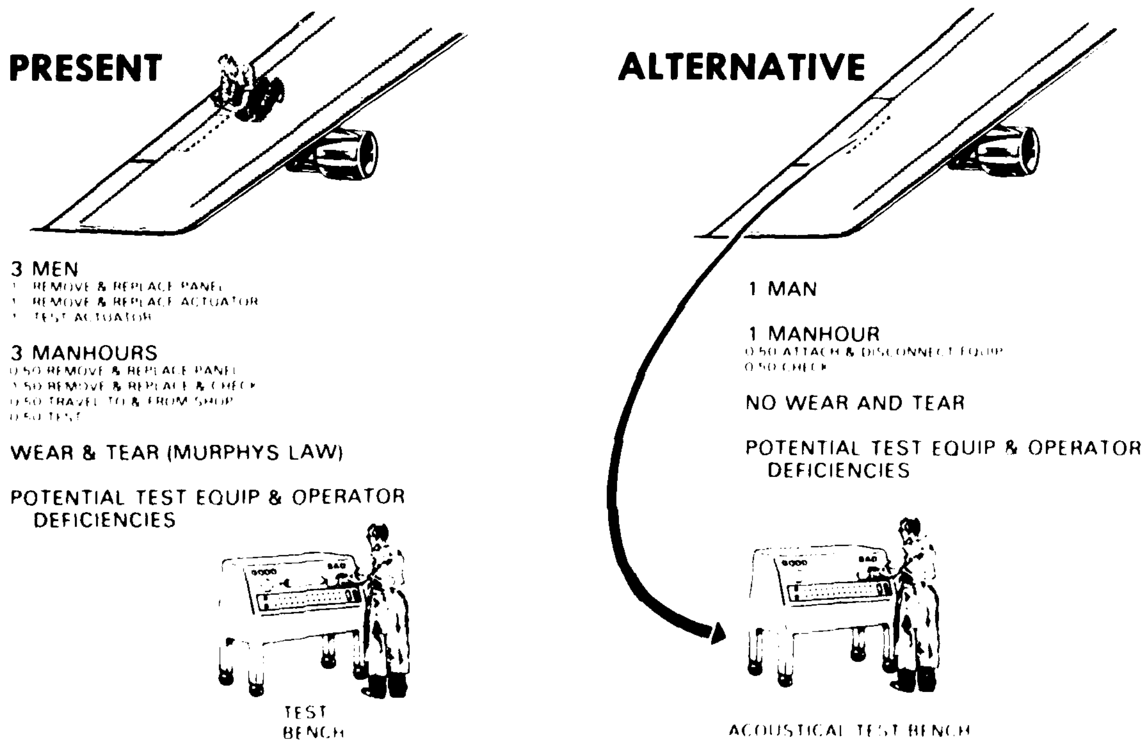


Figure 17. Inspection Concept Hydraulic Actuator Condition Verification

For inspection systems, there are possible technology solutions to deficiencies in the functions shown on the left column, Figure 18. Those technology solutions (opportunities) could fall into the function/system categories of listening, diagnostic, timing, and integration. On the other hand, the best solutions may be procedural. However, procedural technology cannot be separated from system/functions without some initial deficiency/technology assessment.

During this past year, we have looked at a few sample logistics subsystems and modeled the approach for their solutions. Also, we have prepared descriptions of how to include this process in the acquisition programs. It is not an easy research task. It is just beginning to be funded by government and industry. We recommend that research for design of any systems life cycle cost begin with an understanding of the three statements on Figure 19.

It has been a great pleasure for me to participate in this AGARD meeting. I look forward to further discussions on this subject.

Support Subsystem Deficiency/Concept Area	Technology Opportunities: Function/Systems	Technology Opportunities: Policy/Procedures
Inspections	Automated Listening Function-Vehicle Ground Interface	Assessment Procedures Records Function
Assessment		
Timing	Centralized Listening Post Function	Timed Inspection Progression Function
Location		
Degradation	Vehicle Diagnostics Readout Function	Automated Procedures Callup Function
Control		
Repetition	Mechanical	Operating Sequence Critical Identification Function
Allocation	Avionic	
Progression	*Structural*	
Wear	Fluids Detection	
	Time To Go Time Dependency Function	
	Vehicle/Facility Integration Function	

Figure 18. Possible Technological Solutions to Deficient Areas

GAIN UNDERSTANDING BY

- A LOOK AT HISTORY
- A TECHNOLOGY APPROACH TO SOLUTION OF DEFICIENCIES
- STRATEGIZING METHODS OF APPLICATION
  PROGRAMS
  SEPARATE DEVELOPMENTS

Figure 19. Research for Design to Life Cycle Cost

IMPACT ON SYSTEM DESIGN OF COST ANALYSIS OF SPECIFICATIONS AND REQUIREMENTS

Horst Grieser
Dornier GmbH
Friedrichshafen, F.R.G.

AGARD Symposium on DTC and LCC
Amsterdam, 19-22 May, 1980

From 1970 through 1980 the German defence budget nearly doubled, and has reached about DMK 4[illegible] billion.

Expenditures related to R&D and procurement of new weapon systems have shown a steady, but slow, increase and are likely to reach one third of the total budget by the mid-eighties. All other expenditures including, first of all, those for the operation and support of weapon systems have slowly decreased in relative terms, but will still represent two thirds of the total budget, - and are expected to grow in absolute terms. According to the German MoD WHITEPAPER 1979, this trend will be accompanied by an increasing deficit in personnel.

This overall picture can be directly related to individual weapon systems. Typical cost relations for the development, procurement, and operation of a flying weapon system usually lie between 1:3:5 and 1:4:10 (figure 1).

Hence, the success of a new weapon system will decisively depend upon the predicted annual cost for operations and support.

The need to meet weapon systems requirements within natural budget limits therefore tends to result in the establishment of cost as an active design parameter, - in the same sense, and for the same purpose, as effectiveness and schedule parameters.

Figure 2 shows, in a condensed form, the primary elements to be defined by the future user of a new weapon system, and the goals to be achieved on the contractor side, i.e.

- the "Desirable" and
- the "Feasible".

The arrows indicate the dynamics of the process which is to lead to an acceptable common basis, particularly at the very beginning of a new program.

Cost analysis represents a continuous interface between the DESIRABLE and the FEASIBLE. It is generally agreed that cost analysis should be an integral function of SYSTEMS ENGINEERING. Only then will it be possible to "translate" the various kinds of requirements accompanying the realization of a new weapon system.

Four categories of requirements are to be considered (figure 3):

(1) Technical requirements,
(2) Operational requirements,
(3) Program-specific requirements, and
(4) Budget constraints.

Their impact on cost is to be identified and quantified for each phase of a weapon system's life-cycle. To make sure that potential cost drivers coming up further downstream will be identified and eliminated, in time, this process has to start long before the weapon system will become operational.

It is worthwile remembering that by the end of the conceptual phase about [illegible], and by the end of the definition phase about 80%, of life-cycle cost (LCC) are "frozen" by decisions taken with regard to the design and its technical realization.

Therefore, cost analysis should have the following four main objectives (figure [illegible]):

(1) Design support, i.e. cost-oriented evaluation of alternative design concepts;

(2) Contribution to cost-effectiveness trade-offs, i.e. interrelations between unit cost, force size, total force effectiveness, and budget;

(3) Interpretation of one's own cost data in relation to those of competing weapon systems;

(4) Preparation of program-specific data, e.g. manpower needs and annual budgets, or cost related to alternative workshares.

Cost analysis should be transparent and flexible so that relevant cost data may be presented according to varying interests. There are essentiall four questions that use to come up in connection with cost information (figure 5):

(1) What for?.......... Identification of "cost carriers", i.e. generally hardware/results (e.g. airframe, wing, flap)

(2) Where? .... Identification of "cost centres", i.e. functions/tasks (e.g. manufacturing);

(3) Which? .... Identification of "cost categories", i.e. kind of cost element (e.g. manufacturing labour);

(4) When? .... Identification of program phases (e.g. development), or phase segments.

One principle of combining those four interests is shown in figure 6. This cost-breakdown matrix is, in fact, three-dimensional:

- o 2 dimensions are needed to identify cost categories (e.g. labour or material) for defined weapon system elements and defined functions,
- o the 3rd dimension identifies time, i.e. individual program phases.

A classification code makes sure that every cost element, - from the top-level down to the lowest practical level -, can be identified, and any combination of cost elements be arranged according to the kind of information required.

For the definition of work-packages, e.g., it may be of interest to quantify the total cost of a wing, or part of a fuselage, from the first drawing through final assembly. Similarly, engineering cost or manufacturing labour cost may be of interest when it comes to talks about worksharing between main contractor and sub-contractors and, hence, to "design-to-cost" (DTC) goals.

The cost-breakdown matrix for the operational phase looks slightly different, due to the differing interests to be combined.

When one starts to identify and quantify potential cost drivers of the procurement phase it is useful to proceed in a way that is qualitatively shown in figure 7.

Beginning in the centre of the figure, it is assumed here that the total number of aircraft to be procured includes pre-series production aircraft. The dominant portion of the overall procurement cost refers, of course, to the series production aircraft. Going to the next level it is seen that the fly-away cost of the production aircraft represents the main cost element and should, therefore, get main attention with regard to DTC.

A further differentiation of this cost element leads to the airframe to be looked at. Since the procurement cost of the airframe is smaller than the system cost charge it is essential to further split this latter cost element, - by means of which the initial spares are identified as additional potential cost drivers.

Finally, by going to the 4th level it is found that fuselage and engines, alone, are directly responsible for, say, one third of the overall procurement cost of the weapon system. This is where further investigation is necessary to make sure that the original DTC goal will be met, or necessary cost reductions will be realized. G.S.E. and training equipment, too, represent a considerable portion of the total procurement cost.

The small portions of the avionics sub-systems should, however, not lead to the conclusion that avionics cost is of minor importance. It is of the same order of magnitude as engine cost; and, whereas the engine decision is generally made rather early in a program, the requirements concerning the avionics system use to become more and more ambitious, and may lead to unexpected cost explosions.

Figure 8 qualitatively summarizes the cost-sensitivity of major LCC elements. It is shown by how much the cost of each element has to be reduced to achieve the same overall (LCC) improvement.

As can be seen relatively small changes are necessary for operation-orientated LCC elements (e.g. material, personnel, and POL) to achieve a defined/required LCC reduction. For the same effect procurement cost of the avionics system, e.g., would have to be reduced by as much as 80%, - which with regard to the basic requirements and specifications would be an unrealistic approach.

On the other hand, the same effect could also be achieved if, e.g., the development of a new engine could be avoided.

It should be mentioned, however, that the above figure can only be used as a very first decision aid since in reality all LCC elements are more or less interrelated with one another. For example, using an existing instead of a newly developed engine could - but need not - result in higher procurement cost, and could in addition have a negative impact both on M&O and POL costs during the succeeding 15 or 20 years of operation.

Unit procurement cost of a new combat aircraft also largely depends on whether the aircraft will be laid-out as a single-seater or a two-seater. From a cost point of view the price for the second seat may result in a procurement cost increase of between 5% and 20% compared to a single-seater.

On the basis of a given procurement budget this means that instead of, say, 300 aircraft only 280 or even 240 aircraft can be procured. This numerical disadvantage, however, has to be traded against the expected tactical advantage in terms of total force effectiveness.

The eventual cost difference primarily depends on the function of the second seat, e.g. option for training or standard for combat, which should be clearly specified. It also depends on the general design philosophy concerning the technical realization of the second seat, for which a variety of approaches are possible.

If the original requirements is for a single-seater the resulting aircraft unit cost will depend on how rigid this requirement is to be considered in the long run.

If the requirement is expected to change at a later date (may be simply for export reasons) then the aircraft manufacturer can choose between the following possibilities (see figures 9 and 10):

(1) Use of the inherent potential of a single-seater at the acceptance of certain performance penalties. (A small cost increase for the two-seater may, however, result from the fact that the basic single-seater is relatively expensive due to the built-in growth potential).

(2) Complete re-sizing of the basic design to make sure that all performance requirements of the original single-seater will also be fulfilled by the two-seater, e.g. radius of action, weapon load, S.E.P., turn rate, etc.. This is, of course, the more expensive solution.

Requirements with regard to S.E.P. and turn-rate have a decisive impact on the design of a new combat aircraft and, hence, on cost. Each additional degree per second in turn rate and each additional metre per second in S.E.P. can be translated into cost increases; figure 11 shows the influence on procurement cost. Assuming a typical procurement quantity of 300 aircraft a 10% increase in S.E.P. or turn-rate would mean a total cost increase of the order of DMK 300 to 500 million. From a cost point of view it would be worthwile to investigate if such an amount of money should not be better invested for additional aircraft at slightly reduced flight performance.

Figure 12 refers to the avionics system of combat aircraft; avionics systems use to cause the highest specific procurement cost (DMK/kg) and are, therefore, particularly sensitive with regard to changes in requirements/specifications.

In order to help the designer and the project management to better understand these influences it is often useful to provide this kind of information which shows, in quantitative terms, by how much the aircraft fly-away price or total procurement cost (of, say, 300 a/c) can be reduced if 1 kg in weight could be saved. The specific cost of typical avionic subsystems can be as high as 12 000 DMK/kg. A weight reduction of the avionics system can, therefore, be 4- to 6-times more effective than the same reduction in structural weight. The cost saving will in all cases be even greater if the sizing effect of the overall aircraft layout is taken into account.

Another example showing how DTC criteria can influence the choice of a particular hardware item is presented in figure 13.

This diagram shows, in relative terms, the statistical interrelationship between packaging density, volume (weight), and unit cost of airborne computers.

A requirement for more computer capacity can be solved

- either by more weight (or volume) at the same packaging density,
- or by increasing packaging density at the same volume.

The example shown indicates that a 50% increase in packaging density may lead to 70% higher unit cost, whereas a corresponding weight or volume increase would change unit cost by less than 50%.

In spite of the potential cost saving in the latter case, however, the more expensive computer may turn out to be the more cost-effective solution

- if re-sizing effects of the basic design can be avoided, and
- if the more advanced technology leads to improvements in maintainability and reliability, i.e. in O&S cost.

The total spectrum of technical and operational parameters, - together with relevant cost data, are normally evaluated on the basis of Systems Engineering methods, e.g. simulation, models, statistics. Solutions that are consistent with defined DTLCC goals and, of course, with the basic requirements and specifications, will then be forwarded to the project management as decision aids. It is obvious that the methods developed for flying weapon systems can also be applied to other weapon systems and, to a high degree, to non-military systems.

Two other examples referring to potential cost drivers of basic aircraft equipment are shown in figures 14 and 15.

The first figure referring to a typical fuel system of a combat aircraft illustrates that more than 80% of the cost are determined by only four types of components, especially valves and pumps.

Similary, the second figure shows the cost of relevant components of a typical hydraulic system. Again only 6 types of components account for over 80% of the cost.

These are the components that use to be included in DTC considerations, and that DTC goals should be established for, at the earliest possible date.

Experience has demonstrated that DESIGN TO COST (DTC) is an essential tool for the successful realization of a complex, costly, and long-term program. It has become evident that the times of "optimum cost-effecitve solutions" are gone. Such solutions may result in overall cost numbers lying above a cost ceiling that can be afforded, and may eventually lead to the cancellation of the total program.

Industry, too, therefore has to show a vital interest in integrating cost ceilings (cost goals) as program inputs.

Figure 16 shows the interrelationship between

- aircraft size (airframe unit weight),
- fleet size (number of aircraft to be procured <u>and</u> operated for, say, 15 years under peacetime conditions), and
- budget (DTLCC goal).

This figure is based on hypothetical aircraft of essentially the same performance (speed, range). LCC is the total cost for development, procurement, and operation. Cost degression effects for increasing production quantities are included.

The requirement to stay within a limited LCC budget can be satisfied both

- by a small number of <u>large</u> aircraft, and
- by a large number of <u>small</u> aircraft.

Pros and cons can be found for either solution and, normally, cost-effectiveness trade-offs will help to identify the solution with the maximum inherent force effectiveness, - based on a not-to-exceed LCC budget.

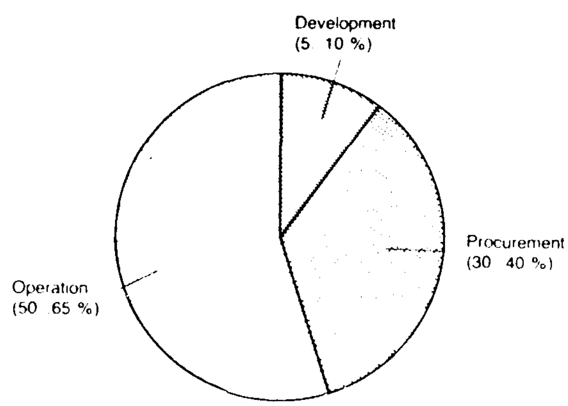
If two alternative aircraft designs of different size are compared, e.g. with 50% difference in airframe unit weight, the resulting fleet size of the smaller (datum) design is about 50% greater than that of the larger design, - at the same LCC budget: this means, e.g., 300 small aircraft instead of 200 large aircraft.

But, the larger aircraft can carry more weapons and, therefore, offers higher unit effectiveness than the smaller aircraft. In addition, the smaller fleet of larger aircraft requires less personnel and less infrastructure, - aspects that may become dominant.

The larger fleet of small aircraft, on the other hand, promises tactical advantages, e.g. due to saturation effects over enemy country. Also the fact that weapons tend to become smaller and more effective favours the solution of a small rather than a large aircraft.

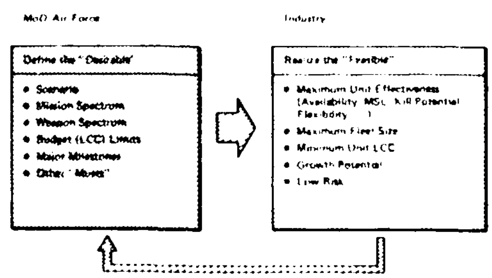
Whatever operational, tactical or political aspects may become relevant during the decision process, - cost analysis will continue to play a dominant role.

FIGURE 1



DORNIER Operation Main Cost Driver

FIGURE 2



DORNIER The Problem

AD-A090 098 ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT--ETC F/G 5/1
DESIGN TO COST AND LIFE CYCLE COST.(U)
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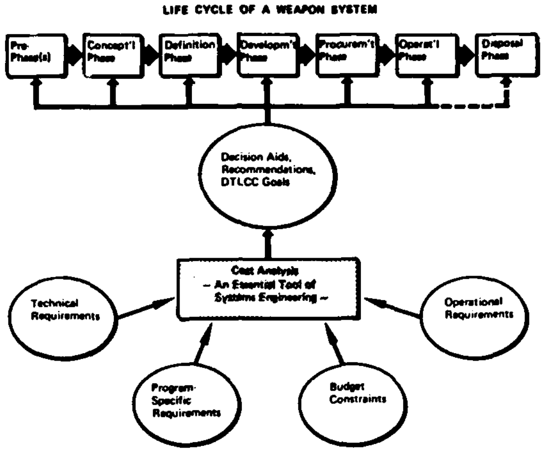
FIGURE 3



DORNIER **Cost Analysis: – Continuous Interface between the "Desirable" and the "Feasible" –**

FIGURE 4

- Design Support
- Contribution to Cost-Effectiveness Trade-offs
- Interpretation of Own Cost Goals Relative to Cost Data of Competing Weapon Systems
- Preparation of Program-Specific Data (Work Packages, Budgets)

DORNIER **Cost Analysis – Main Objectives –**

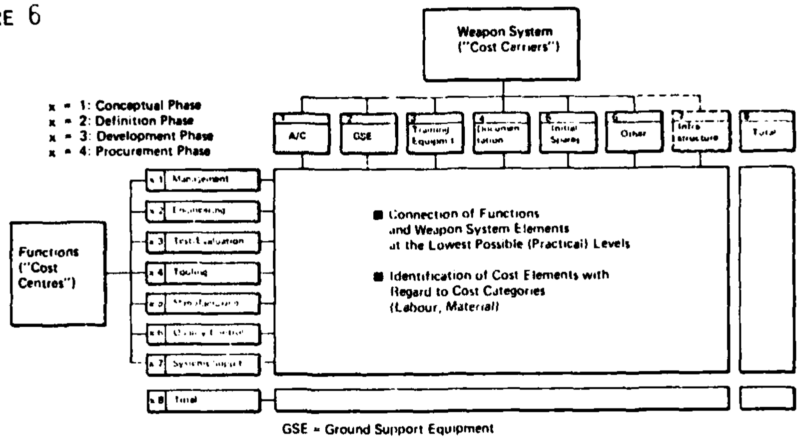
FIGURE 5

Identification and Quantification of Cost Elements with Regard to the Following 4 Questions:

- What for? → Cost Carriers
- Where? → Cost Centres
- Which? → Cost Categories
- When? → Phases

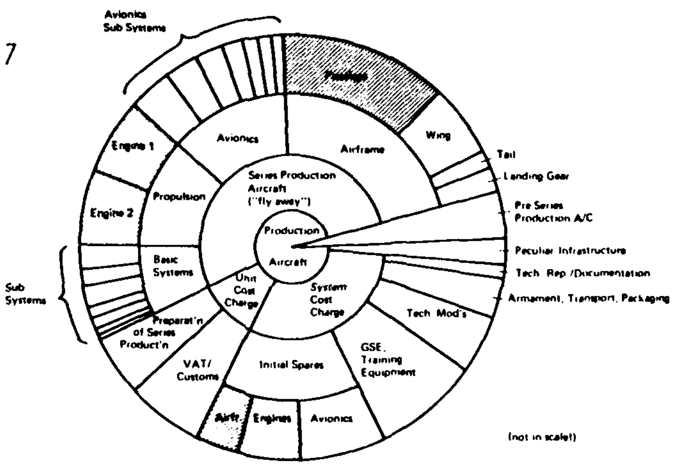
DORNIER **Cost Analysis – the 4 Question Marks –**

FIGURE 6



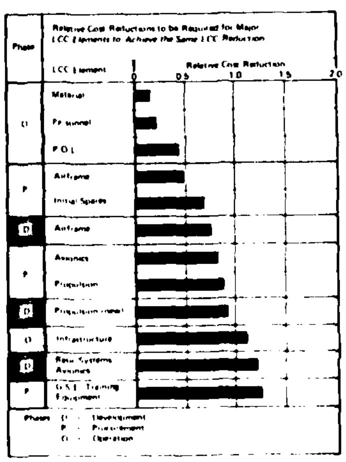
DORNIER **Cost Breakdown Matrix**
– Basis for Transparency and Flexibility –

FIGURE 7



DORNIER **Qualitative Procurement Cost Breakdown**

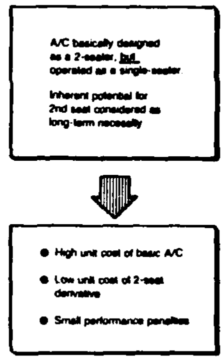
FIGURE 8



DORNIER **Partial Cost Reductions Leading to the Same LCC Reduction**

FIGURE 9

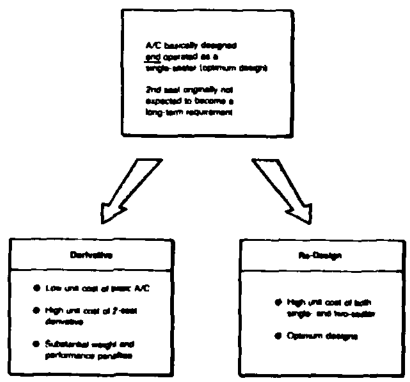
Change in Requirement from Single-Seater to Two-Seater:
- Design Approaches
- Cost Impact



DORNIER Two-Seater vs. Single-Seater (1)

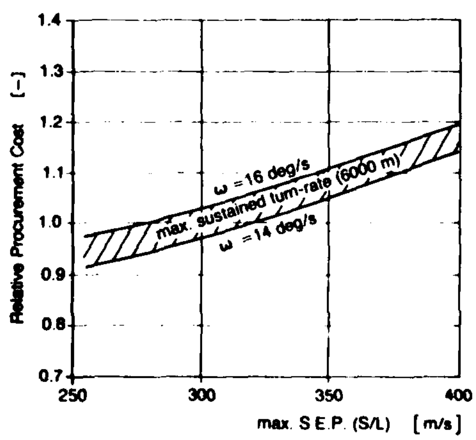
FIGURE 10

Change in Requirement from Single-Seater to Two-Seater:
- Design Approaches
- Cost Impact



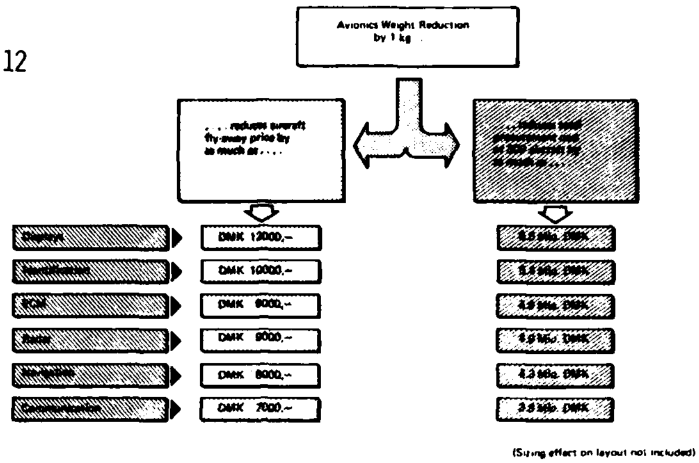
DORNIER Two-Seater vs. Single-Seater (2)

FIGURE 11



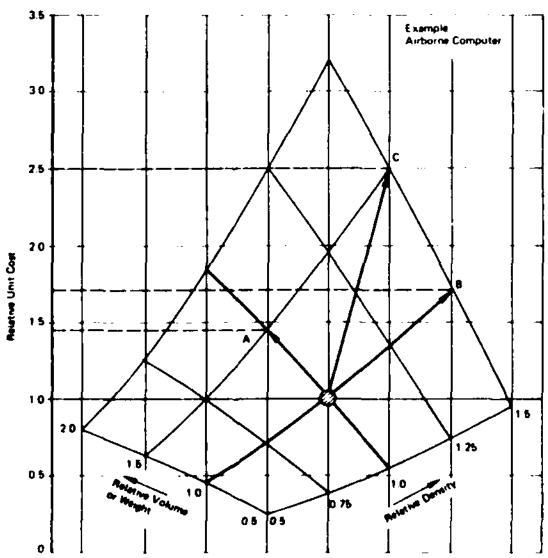
DORNIER Cost-Sensitivity of ω and S.E.P.

FIGURE 12



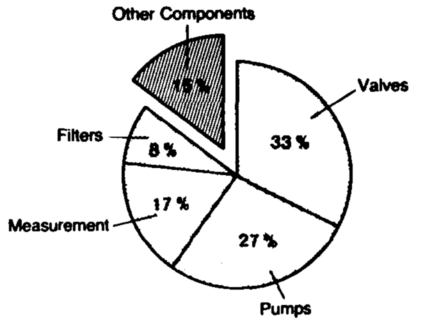
DORNIER Potential Cost Drivers of Avionics

FIGURE 13



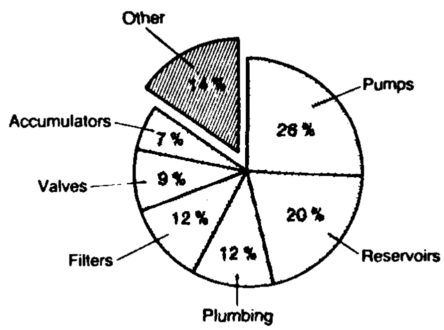
DORNIER Statistical Interrelationship between Packaging Density, Volume (Weight), and Unit Cost (Example)

FIGURE 14



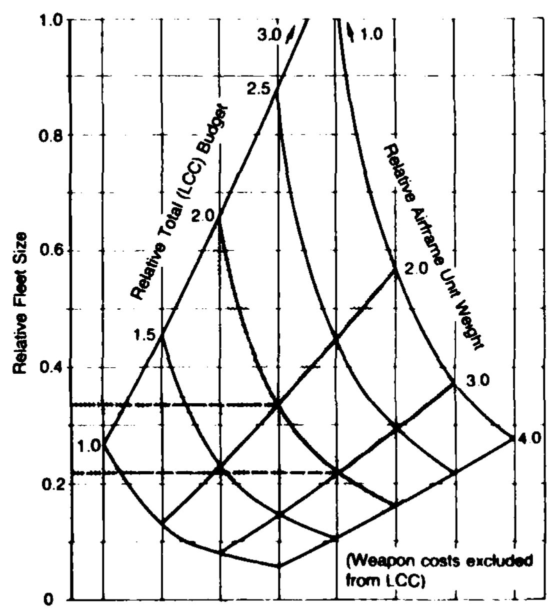
Potential Cost Drivers:
Example: Fuel System of a Hypothetical Combat Aircraft

FIGURE 15



Potential Cost Drivers:
Example: Hydraulic System of a Hypothetical Combat Aircraft

FIGURE 16



Interrelationship between Aircraft Size, Total Budget, and Fleet Size

EVOLUTION OF TECHNIQUES FOR LCC ANALYSIS

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The paper identifies the need to control aircraft Operating and Support Costs, starting with a co-ordinated approach to Life Cycle Cost Analysis during the conceptual design stage. It discusses some of BAe Warton Division's experiences in the development and use of LCC Models. Also it presents the limitations of existing systems together with examples of our current programme of work on this subject.

1. INTRODUCTION

As an introduction to this paper it is important to comment on some of the factors which account for British Aerospace becoming involved in Life Cycle Cost Analysis (LCCA).

In the UK during the 1960's a growing concern developed over the increasing demands of maintaining modern military combat aircraft and the availability levels required for effective peace time training sorties. One problem being an increase in the numbers and level of expertise required, in terms of maintenance manpower and the additional equipment spares levels and consequent financial investment required. At the same time Fig. 1(a) illustrates the effective reduction in the defence budget when related to GNP and hence the squeeze on funds available for Developing and Procuring new Weapon Systems. This reduction in money available has certainly been apparent in the numbers of new aircraft types entering service over recent years, as illustrated in Fig. 1(b).

Obviously within these very tight fiscal constraints the pressure is on to strive for improving performance in all areas. The contractors are subject to severe cost control systems on the Development and Production Phases of major weapon system programmes. There are requirements to improve performance on the various Operating and Support parameters as shown by Fig. 2. However in general terms there has until recently been little formal co-ordination of these efforts to ensure that the optimum cost effective end product is being produced.

Towards the end of the 1960's, the Aerospace Industry was experiencing an increasing involvement in the conceptual design studies associated with the specification of future combat aircraft. As part of these responsibilities a number of computerised parametric models were being developed covering; aircraft configuration, performance and operations analysis. These systems allow a comprehensive analysis of a number of alternative solutions, in relation to a given or anticipated threat, to be studied. Within the Warton Division of British Aerospace it was decided to take this opportunity to develop a Model to perform trade-offs of cost against aircraft performance and also measure the nett cost gains due to improving Operating and Support parameters. This model relied upon a number of individual estimating relationships and experience already available within the Company, which when combined provided a comprehensive set of relationships enabling us to perform cost effectiveness analyses.

At this time there was no formal definition of Life Cycle Cost (LCC) or requests for LCC information from our Government and therefore the parametric models were developed to meet the specific in-house requirements.

In addition to developing the models it was necessary to gain acceptance of them and significant management effort was expended in discussing the concept of Life Cycle Cost Analysis (LCCA) with the Government and other areas of the Aerospace industry. In certain areas this was straight forward since a number of organisations had already been developing their own models. However, in general terms there were problems since the acceptance of LCC usually conflicts with other interests. Examples may be the demand for greater performance and technological sophistication, or various policy dictates, such as fleet strengths, spares provisioning and manning levels. This problem of gaining acceptance of first the concept and then the results of LCCA has been a major item and is dealt with later in the report.

2. ORIGINS OF LCCA

2.1 Cost Elements included in Life Cycle Cost Model (LCCM)

The original LCCM used in the conceptual aircraft design studies was a computerised set of parametric cost estimating relationships covering the list of elements given in Fig. 3. The object of these trade-off studies were to compare the relative differences of each of the aircraft designs in terms of both performance and cost.

Although the terminology used in Fig. 3 reflects specific experience, in general terms the areas of cost appear to be similar to those included in other LCCM's. This is usually only at the macro level, however, since comparisons against other published models suggest that they can be very different in detail definition. Thus great care should be taken in ensuring consistency of LCC when obtained from differing sources. The choice of cost elements included in the model represent the direct areas of programme cost affected by the specific aircraft design.

2.2 Construction of Cost Model

The model was constructed as shown in Fig. 4. The Acquisition costs being calculated first using a model generated from data on previous B.Ae projects. The LCCM then calculates the Reliability and Maintainability ($\bar{R}$ and $\bar{M}$) characteristics of the aircraft, again based on previous experience but with the capability to include technical factors to represent the order of improvements anticipated for the next generation of aircraft. Finally, the assumed utilisation, logistic and maintenance parameters are fed in and the Initial Support and the Operating and Support (O & S) costs generated.

The major constraint when generating the model was the availability of data. For the initial programme costs, information was available on a reasonable number of projects and more importantly the information tended to be in sufficient detail to be able to group homogeneous categories of cost (i.e. Engineering

Design, Testing, Manufacture, etc.). One area which did present difficulties were the Bought-Out costs, since it is only on the more recent projects that Companies have had procurement responsibility and hence cost information on major items of equipment such as Avionics. It is interesting to note that on more recent projects, where the tendency has been for collaborative programmes, Contractors are only responsible for part of an aircraft. Thus to compile the total costs, the Contractor has to rationalise the differing companies/countries levels of cost, including the effect of fluctuating currency exchange rates which has proved particularly difficult.

For the O & S costs, however, the availability of data has been very sparse. The existing systems for recording costs tended to be either very detailed for the specific logistic, engineering control of aircraft in service and not amenable to aggregating data to summarised levels, or it was recorded at the macro level for the overall fiscal planning/control of projects. This is reflected in the model itself where there are twice the number of Cost Estimating Relationships (CER's) for the Acquisition Cost compared with the Operating Costs.

To a large extent the LCC analyst still suffers from inadequate data recording systems for aircraft O & S costs. The work gone into analysing the information systems means that the problems and limitations are now appreciated in more detail and it is possible, therefore, to improve the quality of the output by allowing for its known deficiencies. This is done both subjectively on an individual basis by hand and automatically on large amounts of data via the use of computer. Obviously this still does not fully compensate for the required recording systems and proposals for overcoming the remaining problems are discussed later in the report.

2.3 Initial Applications of LCCA

Having identified the origins of the LCCM some of the initial applications of the model are briefly discussed. The first use of the LCCM was to examine the distribution of costs to determine the significant areas. A typical distribution for an advanced combat aircraft is given in Fig. 5. As expected the O & S costs represent a significant portion of the total LCC bill. The precise distribution can be affected by choice of elements and definition, however, as shown the Acquisition Costs represent 54% of total LCC, the Initial Support 8% and the Operating Phase 38%.

It should be noted that this particular analysis includes the whole cost of industry overheads but none of the MOD/RAF overheads. This is typical of models used to evaluate cost differences of alternative aircraft configurations, since the magnitude of these other areas are not relevant to the choice of project. However when, for example, reviewing future expenditure in order to identify areas for economy then all cost elements should be considered, including the very significant cost of MOD/RAF overheads (estimated to be of the order of 1.8 x the amount spent on buying new aircraft).

Having established the cost distribution it was then possible to evaluate the relative cost of the alternative aircraft solutions to determine what effect the use of LCC rather than initial programme costs would have. Results typical of this type of analysis are given in Fig. 6.

Prior to the advent of LCCA the cost-effectiveness graph would have utilised the initial acquisition cost of the weapon system, Fig. 6(i). Including cost of ownership into the analysis, as shown in Fig. 6(ii), alters the relative importance of certain of the design concepts. For example the structural complexities of VG become less prominent when considered in LCC terms (points 1,3,5). Also modification to existing aircraft may be less costly initially but is far less attractive when including the total cost of ownership (point 7). Also the LCC comparison shows the effect of the second engine for aircraft 5 and 6 in terms of additional repair and fuel costs.

Although Fig. 6 shows how the ranking of aircraft designs can change when analysed on LCC basis, particularly for differing technologies, it also shows the basic problem that the decision maker has i.e. on a cost effectiveness plot which point gives him the best solution.

2.4 Refinements to LCCM

The continued use of the LCCM in aircraft trade-off studies led to improving the model in specific areas to incorporate the required sensitivity to design parameters. One of the areas developed for example was the cost of 'Reserve Aircraft', where the initial programme assumed a constant ratio to the numbers of front line aircraft. Examination of historical data suggested that single engined aircrsft had a higher loss rate/Flying Hour than twin engined. Since the trade-off studies usually included both single and twin engined aircraft the equations were modified to make the numbers of reserve aircraft a function of number of engines/aircraft. There are, of course, many other parameters which account for aircraft loss rate but examination suggested that the remainder were second order terms.

The model was also developed to take further account of changes brought about by Technology, in particular the trend in $\bar{R}/\bar{M}$ improvements with future aircraft, and other innovations such as the effect of modular build of LRU's which had to be accounted for.

Again typical trade-off studies would include existing and new engine configurations, which required analysis of the effect of varying degrees of modularity and TBO growth. Since there was very little experience of what the effect of modular engines was likely to be on O & S costs the CER's were modified using a theoretical mathematical analysis of changes to Spares provisioning and engine repair costs. Subsequently these results have shown close agreement to similar studies carried out by Rolls Royce.

3. EVOLUTION OF LCCA

3.1 Gaining Credibility in LCCA

By the mid 1970's LCC analysis had progressed from our initial in-house studies to form a major part of cost proposal submissions in response to RFP's from our own Government and potential overseas customers.

One of the early stumbling blocks, which to a lesser extent we still suffer from, is the credibility of the LCC estimates. This was due to two reasons: first the lack of consistency of LCC submissions between various contractors and secondly the lack of understanding of how the LCC submissions should be used.

The initial development of LCC methods, carried out by Industry and the Government in relative isolation, resulted in a set of inconsistent submissions typically illustrated in Fig. 7. This particular comparison was supposedly for the same aircraft, assuming the same utilisation, deployment, logistic and maintenance support. After an extensive investigation into both submissions requiring many manhours of effort it was concluded that the main reasons for the differences were the varying assumptions as to which cost elements should be included in the analysis. It is acknowledged that no project manager could use LCC as a basis for choosing between alternative designs whilst inconsistencies of this magnitude are possible, since he would not have the resources available to fully rationalise the differing inputs. In the case of our own Government the short term solution has been for them to do their own analysis, discussing with the contractors their relative inputs to ensure that their methods are reflecting the true merits of the designs. The longer term solution is for further joint development of the models with the programme of work outlined in section 5.

The other problem in gaining credibility for the results of the LCCA is that of understanding what the models are trying to simulate, in relation to existing logistic and maintenance policies.

In certain areas there exists a negative approach to LCC suggesting that cost savings which cannot be realised should not be included in any LCC analysis. This philosophy is consistent with the task of compiling an estimate of the likely budget levels. However in many instances the object of LCCA is not to predict future budget requirements but to provide cost information to be used as part of the decision making process. Used in this way the Project Manager also needs the understanding of how the figures have been compiled in order that he can identify which of the benefits are likely to affect the budget and which are likely to be realised only through enhanced Operability or by changing the existing procurement and support procedures.

It is this lack of knowledge and understanding of how LCC can be used and the corresponding assumptions employed in deriving each set of results, that creates the problems regarding the credibility of the studies.

An important part of understanding LCCA is recognising that in general there are two quite different types of studies. The first approach is to predict likely budget levels for the cost of ownership for a future aircraft project. The important aspects of this task are to ensure that the absolute cost level and corresponding cash flow are reasonably accurate. The assumptions for the exercise would be broad guidelines which are probably independent of the final aircraft configuration. The second requirement is to quantify the effect of differing design aspects, including level of technology, on the relative LCC of the alternative aircraft configurations.

The solution lies in the manager being more aware of the LCC tools available and more specific when defining his requirements in terms of cost information and any programme constraints which should be included in the analysis.

Also ensuring that when the results are submitted that they are sufficiently well defined/qualified so that he can understand how to interpret them.

This problem appears to have been recognised in the UK and there now exists a far closer working relationship between the Contractor and MOD on costing studies and the development of new costing methods.

3.2 Accounting for Effectiveness in LCCA

The LCC of any given design represents only one half of the story. The overall picture has to also consider the relative effectiveness of the aircraft configuration. It is not the intention of this paper to discuss the methods used in calculating aircraft effectiveness since this is a specialised discipline in itself. However it is important to illustrate how differences in relative aircraft effectiveness can be introduced into the LCCA and also point out that agreed definitions and assumptions are as important (if not more so) in calculating effectiveness as when calculating the cost.

The examples given so far in the report have in general assumed a constant fleet size (front line strength) and result in the type of cost-effectiveness graph illustrated in Fig. 6. To decide which of these aircraft offers better value for money is very difficult unless you know how effectiveness and cost rank relative to one another in your decision criteria. For example, is it worth paying the extra cost of configuration 1 relative to configuration 2 in order to achieve the increment in effectiveness.

An alternative approach is to present the picture on a constant effectiveness (hence varying fleet size) basis. This format is illustrated in Fig. 8 where line A is the usual way of expressing the relative LCC assuming constant fleet size. However if for each configuration the number of aircraft required to attain the same level of effectiveness was calculated and the corresponding fleet size used to determine the LCC, then line B would show the relative LCC for each of the configurations to achieve the same level of effectiveness.

The major problem with this approach, of course, is choosing how to define effectiveness since many possible definitions exist. This particular example uses the maximum number of kills per day in the defensive air role assuming intruders penetrating at M = 0.8 altitude 40,000 ft. and continuous operation. Although a host of possible scenarios and assumptions could have been used as the criteria for effectiveness, the extensive modelling routines available on this subject enable us to very quickly evaluate a wide range of alternatives in order to examine the variability of the resulting cost-effectiveness over the range of likely scenarios and mission parameters. This is usually more important than the 'best' solution for a particular scenario or even a 'best mean' value.

3.3 LCCA for Overseas Sales

One of the original criteria for formulating the LCC model was for it to be suitable for use in aircraft conceptual design trade-off studies. This criteria virtually defined the structure of the model, including the choice of cost elements and input variables. As the concern over aircraft O & S costs has become recognised by more and more Air Forces there has been a corresponding increase in the request for LCC information particularly when having to respond to RFP's from overseas customers. In the majority of these cases the aircraft being considered has been in-service for a number of years and the LCC can be compiled by using values actually being recorded. However when dealing with aircraft types which have not been in service long enough to demonstrate their cost of ownership the available data has to be supplemented with the use of some form of LCC model. For these applications a model has been constructed enabling trade-offs peculiar to this type of problem to be carried out. In general, the trade-offs on aircraft technical parameters are limited to relatively minor modifications to the aircraft. The majority of trade-offs tend to be in terms of aircraft Utilisation, Deployment and Support Philosophy. Note that for existing aircraft the model outputs have to fit any published data.

3.4 Summary of Major Arisings

To summarise some of the main points emerging from the evolution process, we have:-

(i) it is important to achieve credibility in the LCC estimates. This can be achieved by education and discussion with both contractor/MOD.

(ii) LCC should not be considered in isolation, the LCC studies have to be viewed from an overall cost-effectiveness point of view.

(iii) The concept of a comprehensive LCCM for universal application is not practical, the possible useful applications for LCCA is increasing all the time and models have to be continually developed to suit the requirements of each individual problem.

4. EXAMPLES OF LCCA/COMMENTS ON CURRENT STUDIES

Earlier sections have indicated the general formulation of the models, how they have developed and their general use in aircraft configuration trade-off studies. However, this is not the sole use of LCCA and this section tries to illustrate the scope of application by describing somewhat differing applications of LCCA.

4.1 Use of LCCA in $\bar{R}$ & $\bar{M}$ Analysis

The first example is a study to determine the likely LCC savings due to introducing a $\bar{R}/\bar{M}$ enhancement programme to a new aircraft project. The LCCM was used to determine the important cost drivers and to then quantify the effect of the adopted strategy.

The analysis of the Acquisition phase was carried out at Work element level (e.g. Design, Testing, etc) and the Operating phase at system level (e.g. Airframe, Equipments, Avionics).

Some of the major points arising from the analysis are illustrated in Fig. 9. These are:-

(i) Vendor costs, which are proportional to the number of components included in the $\bar{R}/\bar{M}$ strategy, are a significant proportion of the additional investment costs. Optimum LCC gains can be achieved by selecting 15-20% of the components.

(ii) Airframe $\bar{R}$ testing of components should be applied only to the minimum number of components, selection being justified on a cost-effective basis.

(iii) $\bar{R}$ improvements gave greater LCC savings than $\bar{M}$.

Some of the trade-offs were infact too detailed for existing models and these had to be supplemented with a subjective analysis. This was especially so for analysis at LRU level. This latter shortcoming in the programme has since been rectified by developing another system which allows trade-offs at LRU level of $\bar{R}$, MTTR, Testability and Logistics support concepts.

Two additional facets to the analysis were:-

(i) to quantify the resulting change in effectiveness (in this case measured as wartime sortie generation)

(ii) to investigate the effect on cost saving of delaying the decision to change the logistics support levels.

Fig. 10(a) illustrates the benefit of improved effectiveness and how the result varies with the definition of effectiveness. The method of calculation was very similar to Fig. 8 where the benefits of improved $\bar{R}/\bar{M}$ were converted into a reduced fleet size in order to maintain constant effectiveness. Fig. 10(b) illustrates the rate of cost saving over the life of the project. The point to note is that the logistic and maintenance support policies have to be changed in order to realise the cost savings and the later this decision is taken the lower the actual cost reduction will be.

As a further point of discussion on this item, the sensitivity analyses performed using the model confirmed the need to improve $\bar{R}$ and $\bar{M}$ values in order to reduce the O & S costs of future aircraft (Fig.11). However they also showed the need for careful housekeeping and project control throughout the life of the aircraft. Fig.11 shows how O & S cost savings achieved through dedicated and costly design to improve $\bar{R}$ & $\bar{M}$ can be wasted. For example, delays in the repair cycle of defective LRU's, or insufficient fault diagnosis before removing a LRU from the aircraft. It is not suggested that the absolute order of these costs is very accurate since this particular model limits the amount of interaction between variables.

However to a first order of magnitude it does indicate the sensitive areas and parameters.

4.2 The use of LCCA to Optimise 'ircraft Training Fleets

Here our task was to analyse a current pilot training programme and to determine which mix of aircraft meets these requirements with minimum LCC. The major variables included in the analysis were aircraft utilisation, relative LCC and effectiveness (in terms of Number of FH/course, student drop-out rate).

The approach was to:

(i) carry out a sensitivity analysis to identify the high cost areas and to ensure that the model was not over simplified on these elements.

(ii) Calculate the relative LCC of alternative fleet mixes.

The type of results obtained are shown in Fig. 12.

Although this particular analysis was purely an in-house study this approach has been used successfully by Rhein Flugzeugbau GmbH as part of their official submissions on the FAN TRAINER.

4.3 The Use of LCCA in Budget Costing vs Opportunity Costing

Finally an example chosen to demonstrate the difference in philosophy between Budget costing and Opportunity costing.

The object of this study was to illustrate the potential cost savings available if policy dictates could be optimised to a specific aircraft configuration. If required this type of analysis can also illustrate how the 'extra' investment would improve the effectiveness of the aircraft.

The major differences between the two aircraft included in the analysis was the choice of power plant; Config. A had two existing modern turbojets of modular construction, Config. B had a single uprated engine of an earlier technology.

Two methods of costing were assumed (See Fig. 13): (i) CASE 1 - assumes constant fleet size, spare engines and manning levels and hence any differences in LCC are due in the main to the relative UPC. This approach is consistent with establishing an overall budget for a new project. (ii) CASE 2 - assumes differing reserve aircraft for single/twin engine attrition, fewer spare engines for the modular concept and improved TBO growth for existing engine.

This approach is termed 'Opportunity Costing' since the theoretical cost differences, which are a function of the design parameters, assume that the various support policies can be changed as required.

The results of the two approaches are shown in Fig. 13 and it can be seen that too broad an approach to LCC can result in overlooking significant cost differences between alternative configurations. One significant conclusion illustrated by the above example is that when doing an LCC study it is particularly important to look at the high cost areas, to ensure that the model being used is sensitive to the design differences.

Also without identifying these differences on the cost of ownership via a LCCA it would not be possible to plan ahead and change the support policy to realise the cost savings of CASE 2 and would infact probably end up at the levels indicated in CASE 1 whatever configuration was chosen.

5. CURRENT STUDIES

Obviously we are continually involved in LCCA studies on a wide variety of applications, as indicated in section 4. In addition to these studies, however, we are also heavily committed to improving our overall LCC modelling capability, in particular to increasing both Industry's and MOD's understanding and hence confidence in the methodology and therefore in the results, (it has been mentioned earlier in the report that consistency of submissions and credibility in the results have been major obstacles in the use of LCCA in decision making process).

LCC falls into the two major areas of Acquisition and Operating. The methods of estimating the Acquisition phase costs have evolved over a number of years and although we do not have common cost models we do know how in general other various organisations put their costs together and can identify differences between submissions in detail. We are, therefore, tending to concentrate our studies on the development of O & S cost models where the situation is somewhat less satisfactory.

5.1 Development of LCCA

The main headings of the programme of work on which we are currently involved are as follows:

5.1.1 Establish a cost breakdown structure and define terminology - This is one of the fundamental items in understanding LCC. Our objective is to construct a cost breakdown structure for the Operating and Support phase which is as comprehensive as the system used to control the spend in the Acquisition Phase. This means we have to expand the number of elements at the Levels 2 and 3 shown in Fig. 14 and to define the work content of each.

It is not anticipated that all models would include all elements but that the structure of the model would be consistent with the task to be studied. For example, an analysis of engine change times need not include any elements associated with the Airframe and Avionics.

5.1.2 Reference System

It is important to understand what goes into LCC, and why it is being done. To do this a reference system needs to be established to identify the areas given below:-

(i) Utilisation plan - assumptions regarding how aircraft are operated during their service life, e.g. changing role, modifications, etc..

(ii) Maintenance and Support Concepts - (a) Opportunity Cost or Budget Cost - (b) constraints or changes to existing operating policy which are relevant to the exercise.

(iii) Fiscal Constraints - how to compare alternative proposals when they occupy differing time frames. e.g. cash limits on any particular year within the analysis.

5.1.3 Cost Model Development

Ensure that the models are consistent in their use and in meeting the objectives of the study. The starting point for this part of the study is the reconciliation of existing LCC models, using the better points from each to form agreed systems.

5.1.4 Review Information Systems

One of the problems in developing CER's for O & S costs has been the lack of actual cost data available in a usable form. Already a considerable amount of work has been done in the UK in terms of revising information systems and developing 'filtering' systems for clearing data.

We are continually involved in suggesting improvements we would like to see to existing systems.

Obviously the above tasks are not going to be completed over night but we do have the commitment of both MOD and the Aerospace Industry to work together in achieving these objectives. It is reasonable to assume, therefore, that the role of LCCA on the decision making process within the UK will become more prominent as the credibility of the studies increase and that this in turn will result in the reduction in O & S costs to which everyone is working.

6. CONCLUSION

The need to control the Operating and Support costs of future projects at the conceptual design stage has now become an accepted fact. However, it has to be approached in a co-ordinated manner in order to achieve maximum effectiveness. This report has illustrated that LCCA provides a means of assessing the overall cost implications and the whole range of design considerations which lend themselves to this approach.

The primary problem restricting the use of LCCA to date has been the lack of confidence in the results due to the lack of understanding in the methods used. This has been recognised and a major part of our future work is designed to overcome this problem.

B.Ae itself has recognised the usefulness of LCCA for the last 10 years or so and hence its designs will reflect the benefits of this in terms of reduced LCC. Its commitment to the continued development of LCC applications, through all levels of design studies, will ensure that they remain at the fore in this field.

NOTE

The views expressed in this paper are those of the author's and do not necessarily represent those of British Aerospace.

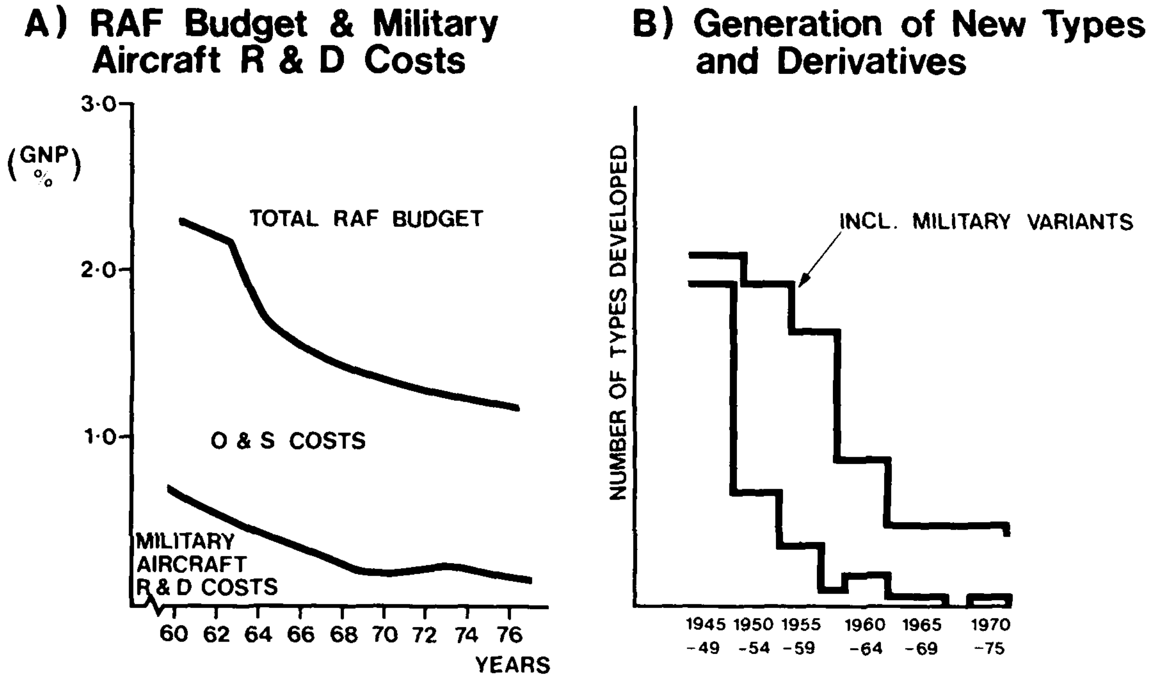

Fig. 1

Variation of Operating & Support Parameters with In Service Date

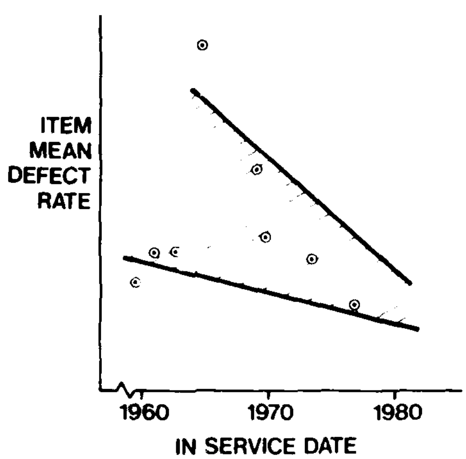

Fig. 2a

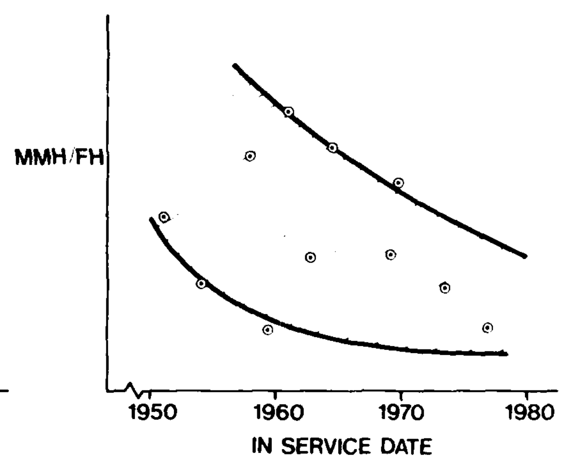

Fig. 2b

List of Cost Elements Inc^{L} in LCCM

Acquisition	**Initial Support**	**Operating Support**
Development	Initial Spares	Repair, Overhaul,
Production Investment	Initial Consumables	Replenishment Spares
Series Production -Front Line AE -Reserve A/c	Age	Replenishment Consumables
	Training Equipment	Fuel
		Maintenance Manpower
		Aircrew

Fig. 3

Life Cycle Cost Model

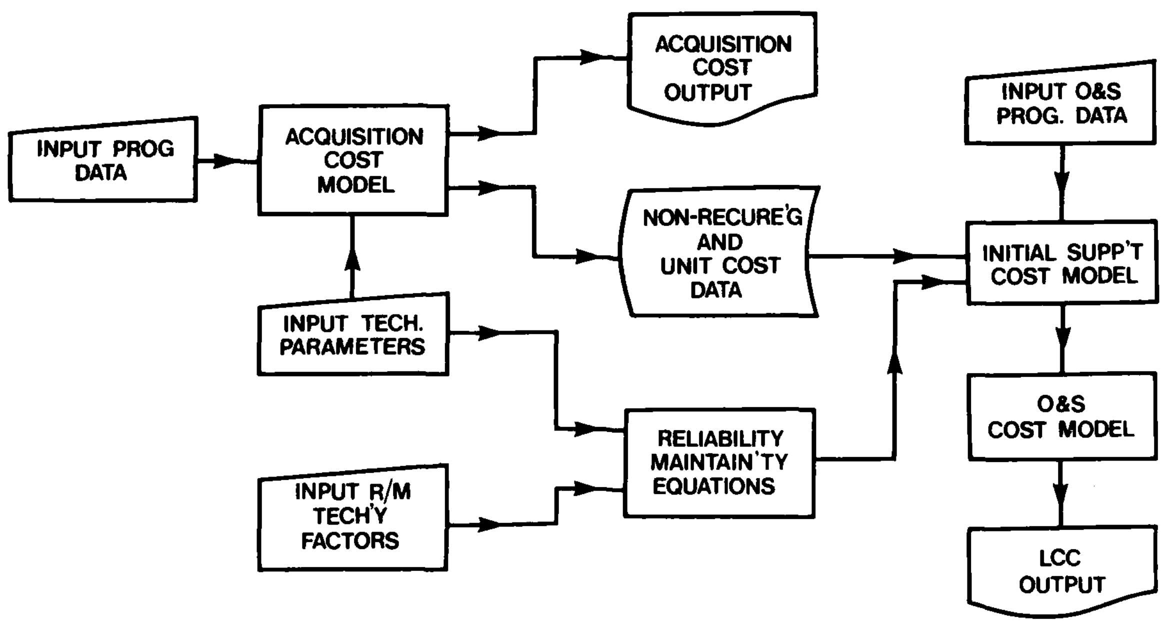

Fig 4

Distribution of Direct Life Cycle Costs

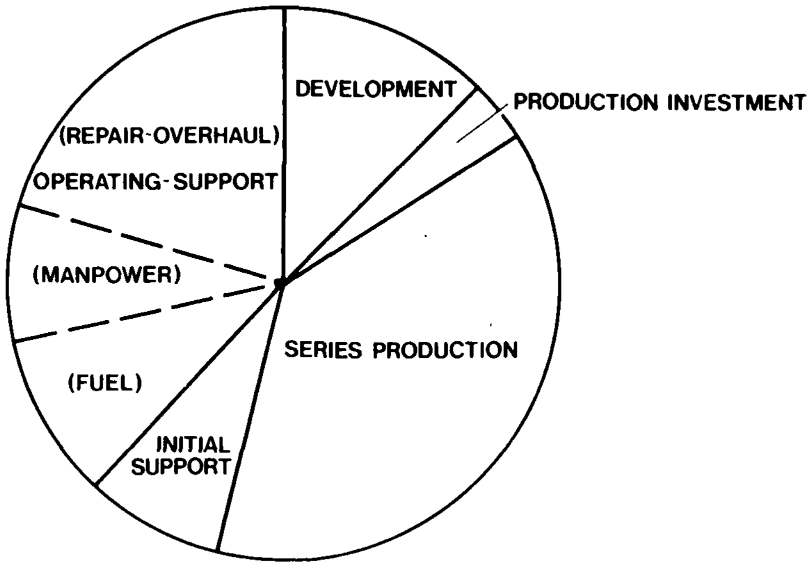

Fig. 5

Relative Cost Effectiveness Ranking Using Different Cost Datums

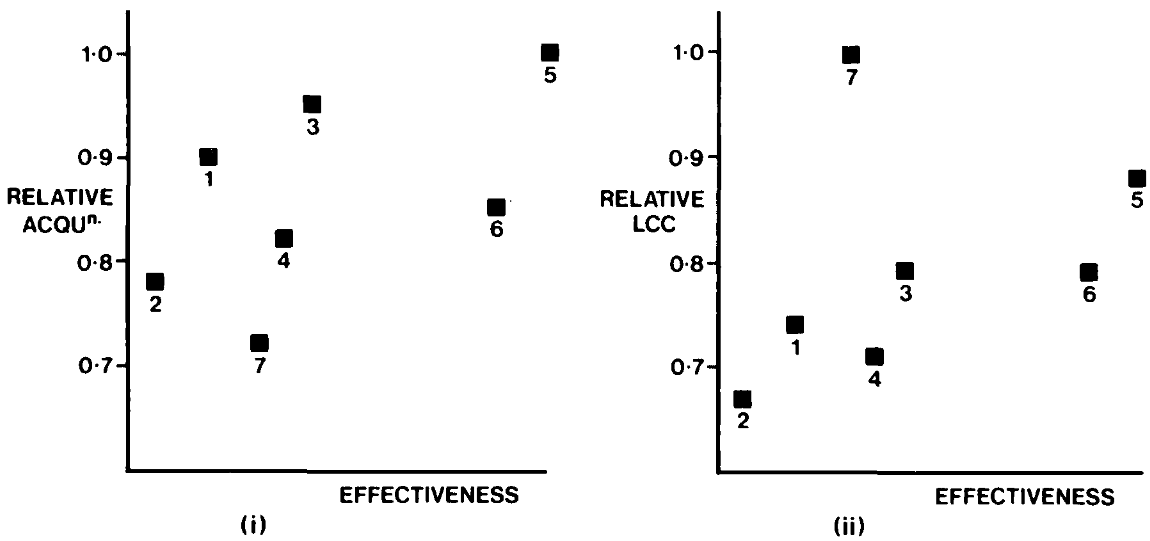

Fig. 6

Example of the Effect on Cost Inconsistencies in Current LCC Submissions

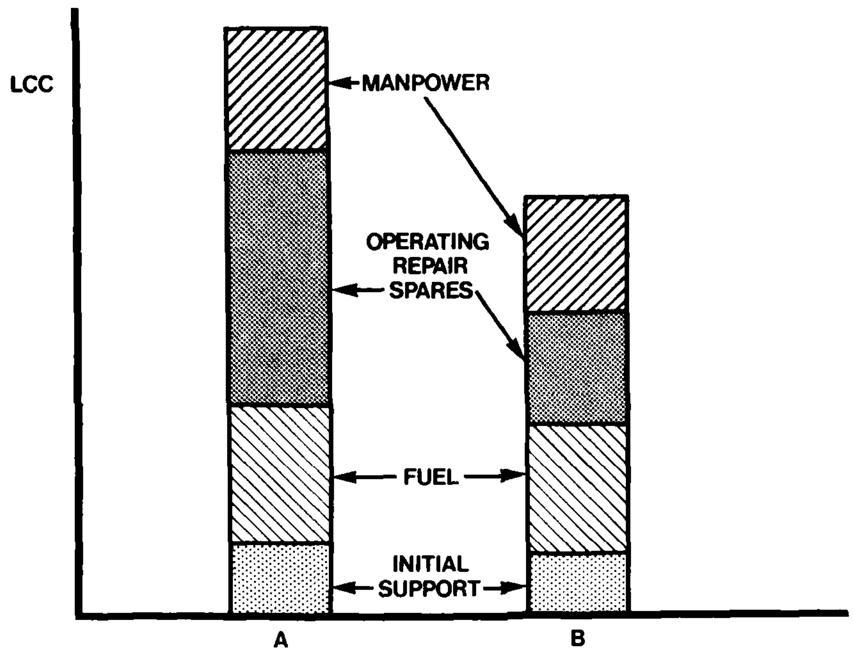

Fig 7

Relative LCC Assuming Constant Effectiveness Versus Constant AE

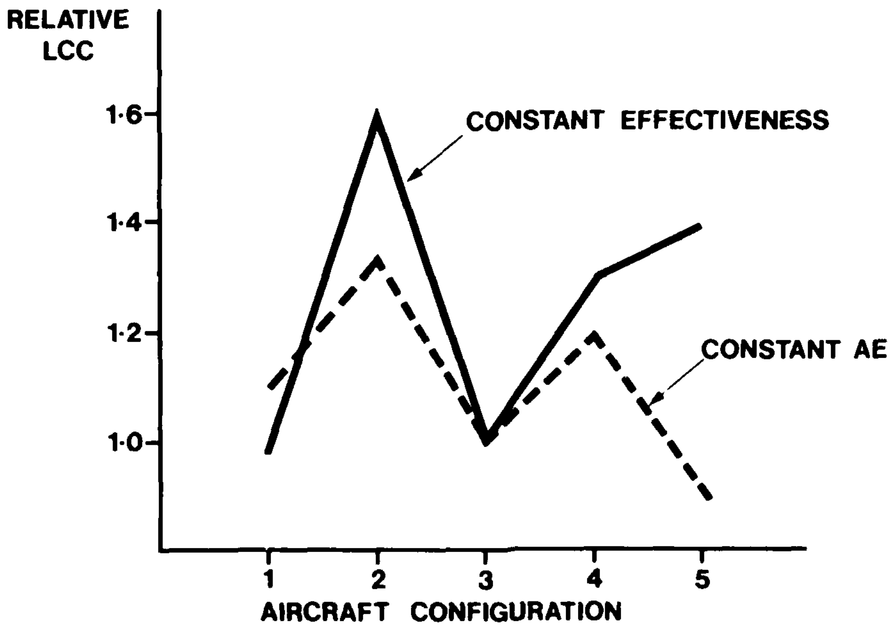

Fig. 8

Typical Results From R & M Enhancement Analysis

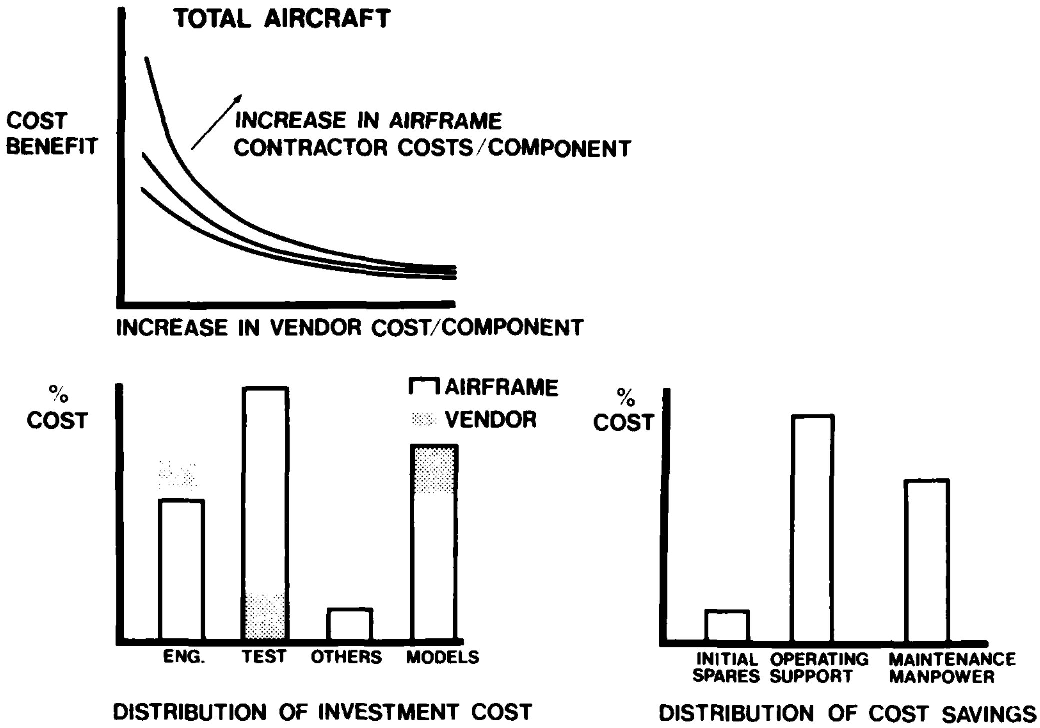

Fig. 9

Additional Results of R̄&M̄ Study

Effect of Including Mission Effectiveness In Analysis

Rate of Cost Saving Due to R̄ & M̄ Enhancements

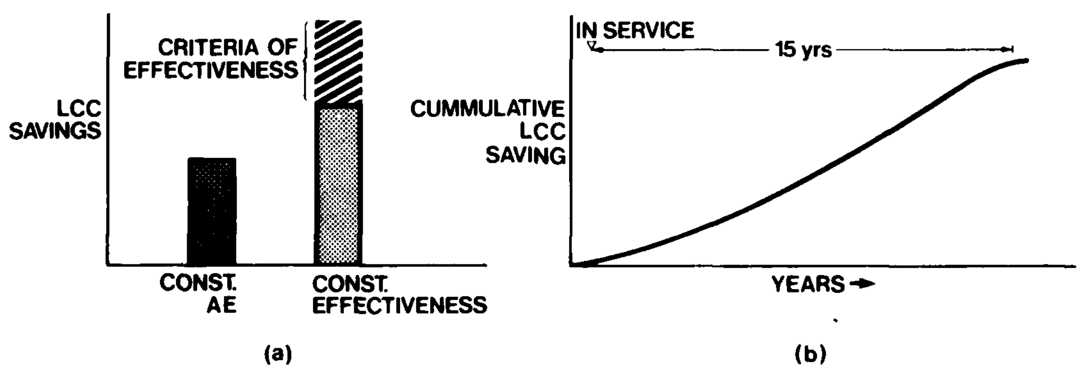

Fig 10

Variation of LCC with Arising Rate and Turnround Time for Spares

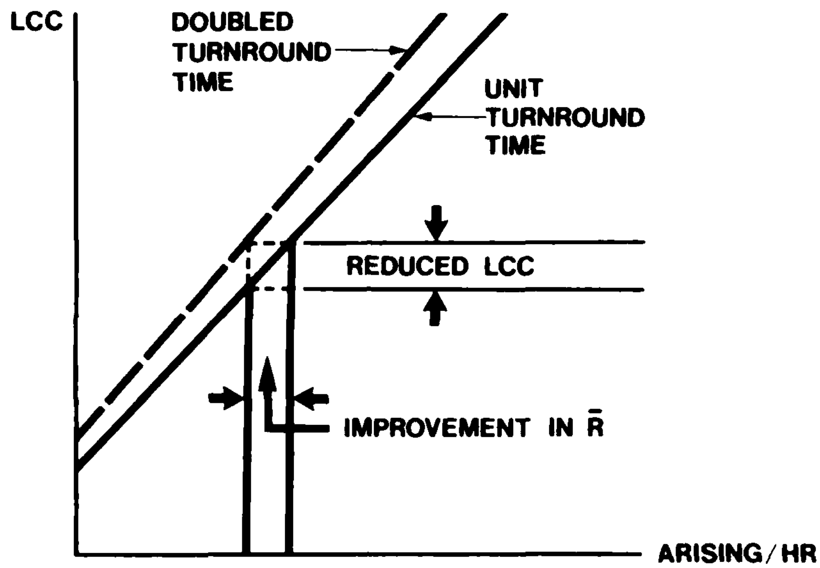

Fig. 11

Pilot Training Simulation
With a Training Fleet of 2 Types of Aircraft

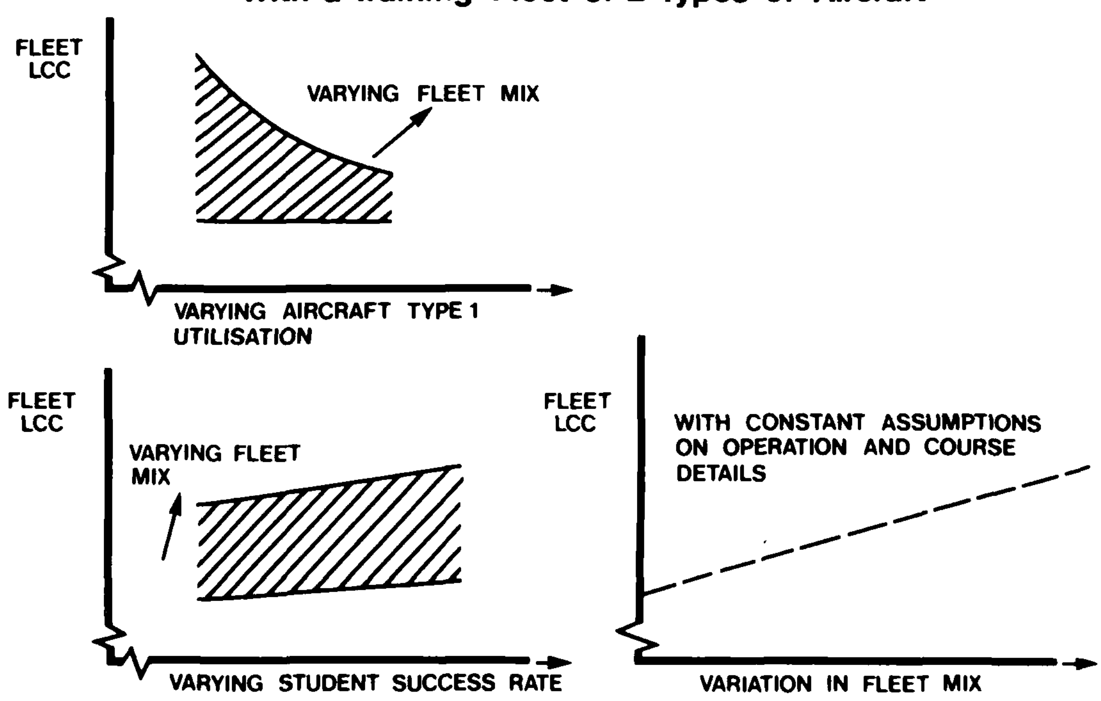

Fig. 12

Effect on Relative LCC of Varying Logistic Support Assumptions

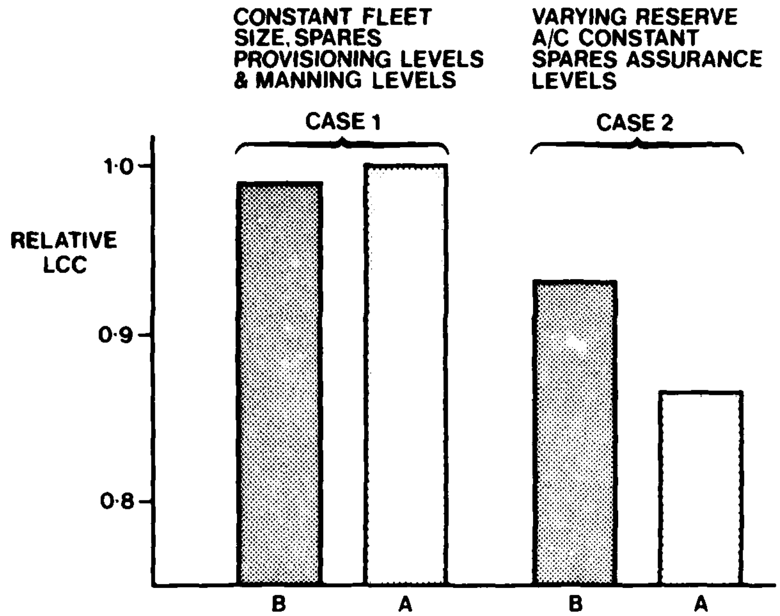

Fig. 13

Cost Breakdown Structure Operating-Support Phase

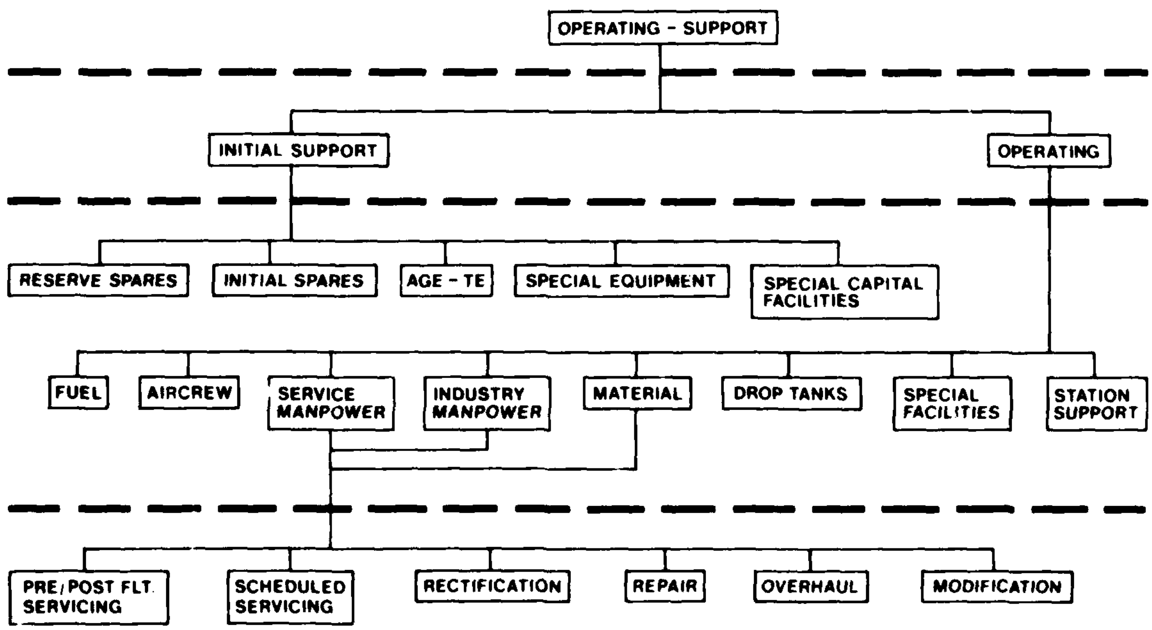

Fig. 14

THE HORNET PROGRAM
A DESIGN TO LIFE CYCLE COST CASE STUDY

by
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Abstract

A primary requirement of the Hornet program is significant reduction in life cycle cost (LCC) from current Navy systems. This paper describes the design and management techniques used by the Navy and McDonnell Aircraft Company (MCAIR), the Hornet prime contractor, to develop a new fighter/attack system at an affordable life cycle cost.

Much of the Hornet program's success in LCC control can be credited to firm Navy reliability (R) and maintainability (M) requirements which the contractor has guaranteed to meet during Full Scale Development. Another important program feature is the substantial R, M, LCC, and program management incentives (totaling \$39 $\bar{M}$) which MCAIR can earn.

Designing to life cycle cost requires the designer to consider key elements of LCC (R, M, unit production cost, and logistics support cost elements such as GSE, spares, training, etc.) in parallel with his traditional concerns with weight and performance. MCAIR's multi-disciplined trade study process accommodates all relevant LCC considerations. Examples of trade studies resulting in relatively large LCC avoidances are summarized in this paper. LCC avoidances of almost \$260 million have been documented to this point in the Hornet program.

Another key LCC control technique is designing and testing to a realistic operational mission environment (OME). Consideration of LCC factors in the supplier selection process has also resulted in large cost savings.

The Hornet will significantly reduce operating and support costs as shown by comparison with the O&S costs of the F-4J and A-7E. The paper concludes with a summary of lessons learned during the Hornet program.

Introduction

In the early 1970s the U.S. Navy began to plan to replace both the F-4 fighters and A-7 light attack airplanes in the fleet. The original Advanced Navy Fighter (ANF) study program evolved into the Naval Air Combat Fighter (NACF) program which led to the F-18 Naval Strike Fighter. McDonnell Aircraft Company (MCAIR) is the prime contractor for this program. The Hornet uses two General Electric F404 engines. Major program objectives and features are summarized in Figure 1.

PURPOSE

- REPLACE F 4 NAVY FIGHTER
- REPLACE A 7 NAVY ATTACK
- REPLACE F 4 MARINE FIGHTER/ATTACK
- IMPROVED READINESS, LOWER OWNERSHIP COSTS

MILESTONES

- FIRST FLIGHT NOVEMBER 1978
- DSARC III APRIL 1980

CONTRACTORS

- MCDONNELL DOUGLAS AIRFRAME PRIME CONTRACTOR
- NORTHROP AIRCRAFT AIRFRAME MAJOR SUBCONTRACTOR
- GENERAL ELECTRIC F404 ENGINE PRIME CONTRACTOR

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FIGURE 1. HORNET PROGRAM SUMMARY

The F-18 requirement was generated, in part, as a reaction to the excessive operating and support costs being experienced by the U.S. Navy's operating forces. A corollary consideration was the need to improve the operating fleet's operational readiness. Therefore, with the Hornet program the U.S. Navy initiated contracting for improved reliability (R) and maintainability (M) and reduced life cycle cost (LCC).

The F/A-18 Hornet is a single-seat, high-performance, multi-mission aircraft which will replace the F-4 in the Navy's fighter role and the A-7 in the Navy's light attack role, as well as replacing the Marines' F-4s in their fighter/attack role. It will provide the fleet with large improvements in air combat maneuvering performance and weapon system capability relative to the F-4 and better weapon delivery accuracy and greatly increased survivability relative to the A-7. For the first time, a high-performance aircraft has been designed for both fighter and attack capability at its inception. The F/A-18 is designed with full fighter and attack commonality. That is, there is only one basic aircraft configuration in both hardware and software. The aircraft in squadron service will be missionized for fighter or attack roles through the selection of external sensors and stores. In addition to the obvious life cycle cost advantages of one airplane for two different missions, the operational commander will be in control of a more versatile and flexible force than in the past.

Now, as the Hornet enters the flight test phase of its development, seems an appropriate time to review this program's emphasis on improved R and M, and reduced LCC. First, the U.S. Navy's program requirements and incentive structure are described. Next, the F/A-18 design features which contribute to significant R and M improvements, relative to the current operating fleet, are reviewed. Lastly, key MCAIR management techniques to reduce O&S costs are discussed. The results of these combined efforts are greatly reduced operating and support costs for the Navy's newest aircraft.

DTC/LCC Incentives

A new contracting initiative adopted by the U.S. Navy for the Hornet program was the use of incentives covering all elements of life cycle cost. The importance of incentives for motivating the contractors to control both production and operating plus support costs is emphasized by the relative magnitude of these cost categories in Figure 2.

Development cost incentives are commonly used, but provide motivation to reduce only about 10 percent of the total costs. A specific incentive to control production costs is a new approach, at least to MCAIR. The Hornet's design-to-cost (DTC) incentive structure is designed to control about one-third of the LCC. Motivation to reduce initial support and operating cost categories is provided by specific R and M incentives.

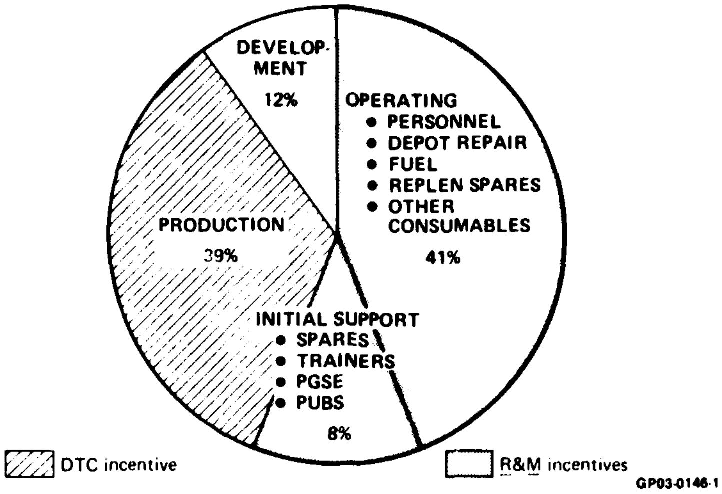

FIGURE 2. HORNET LIFE CYCLE COSTS

The Navy has provided substantial incentives for cost control in the full-scale development (FSD) contracts with both McDonnell Aircraft and General Electric. MCAIR's contract incentives are summarized in Figure 3. The development cost incentive is a typical 80/20 share ratio, with the contractor liable for 20 percent of the variance from the target cost. The design-to-cost incentive is an award/penalty approach. MCAIR stands to earn, or be penalized, 15 percent of the difference between the negotiated production contract target for the first 219 production aircraft and the DTC objective established at contract go-ahead. This DTC objective is adjusted to then-year dollars by applying the appropriate inflation indices. Qualitative life cycle cost/program milestone management incentives and quantitative R and M award fees are outlined in Table 1.

MCDONNELL DOUGLAS

- DEVELOPMENT COST INCENTIVE = 80/20 SHARE RATIO, VARIANCE FROM FSD TARGET COST
- DESIGN-TO-COST INCENTIVE = 85/15 SHARE RATIO, VARIANCE FROM DTC OBJECTIVE
- LIFE CYCLE COST/PROGRAM MILESTONE MANAGEMENT AWARD FEE ≤ \$15,000,000 JAN 76 - JAN 81
- RELIABILITY AND MAINTAINABILITY AWARD FEE ≤ \$24,000,000 EARLY 1980 TO EARLY 1982

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FIGURE 3. FULL SCALE DEVELOPMENT CONTRACT INCENTIVES

TABLE 1. HORNET LCC INCENTIVES
Potential Award Fee = \$39 M

	1200 FH	50 FLT R DEMO	2500 FH	9000 FH
MEAN FLIGHT HR BETWEEN FAILURE	\$4 M	\$8 M		
MMH/FH, "O" LEVEL UNSCHEDULED	\$1.5 M	\$2.5 M	\$2.5 M	
DIRECT MMH/FH			\$1.5 M	\$2.5 M
MEAN FLIGHT HR BETWEEN MAINTENANCE ACTION			\$1.5 M	\$2.5 M
LCC AND PROGRAM MANAGEMENT	\$15 M AWARD FEE BASED ON QUALITATIVE EVALUATIONS AT 6-MO INTERVALS THROUGH 1980			

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Reliability incentives totaling $12 million can be earned at 1200 flight hours and at the completion of the 50-flight R demonstration. Maintainability incentives, also totaling $12 million, can be earned during the first 9000 flight hours. A potential of $15 million in incentives can also be earned by exceptional performance in LCC and program milestone management. These awards are based, at six-month intervals, on qualitative evaluations of the contractor's performance in such areas as:

LCC Management

- LCC reduction achieved during FSD
- Effective application of trade-offs
- Achievement of R, M, and production costs to minimize LCC
- Control of subcontractor's LCC
- Effectiveness in resolving LCC problems
- Evaluation of high LCC contributors
- Acceptability of logistic support analysis program
- Optimization of personnel requirements

Program Milestone Management

- Accomplishment of critical milestones
- Achievement of DTC goals
- Schedule, labor, and material variance
- Plans for achieving system performance requirements
- Substantiation of accomplishments at design reviews
- Management responsiveness in evaluating problem areas
- Satisfaction of management reporting requirements
- Effectiveness of interface management

The U.S. Navy advises the contractor of the weighting of these qualitative factors in advance of each six-month evaluation period, as well as specific criteria to be evaluated in each area. A mid-term evaluation and final evaluation are provided to the contractor for each six-month period.

Since the Hornet's reliability will be largely determined by the performance of its subsystems, it was decided also to provide incentives for major subcontractors and equipment suppliers. A total of $17 million is available to these subcontractors. Prior to the accumulation of 1200 flight hours, most award payments will be based upon qualitative factors, such as LCC management. Beyond 1200 flight hours, most incentive payments will be based on quantitative values of demonstrated R and M. Some subcontractors also have part of their incentives based on laboratory demonstrations of their equipment.

Implementing LCC Management

MCAIR recognized the U.S. Navy's "New Look" requirement to significantly reduce the Hornet's LCC as extremely ambitious. These requirements necessitated many changes from "business as usual" in both the Navy and contractor organizations. Major changes included contractual DTC and LCC requirements and incentives, R and M guarantees (instead of goals), and tracking of LCC changes resulting from trade study decisions or program ground-rule changes. Some highlights of this "New Look" in LCC management are presented in Table 2.

TABLE 2. NEW LOOK IN LCC MANAGEMENT

- LCC REQUIREMENTS ARE CONTRACTUAL INTEGRALLY TIED TO DTC AND ILS REQUIREMENTS
- FIRM DTC UNIT PRODUCTION COST OBJECTIVE WITH INCENTIVES
- INCENTIVES PROVIDED FOR LCC MANAGEMENT AND CONTROL
- FIRM RELIABILITY AND MAINTAINABILITY GUARANTEES WITH INCENTIVES
- LCC BASELINE ESTABLISHED EARLY AND CONTINUOUSLY TRACKED
- LCC SCENARIO AND GROUND RULES DEFINED BY THE NAVY
- LCC ESTIMATING TAILORED TO DESIGN DETAIL

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MCAIR's key management decision in response to the U.S. Navy's "New Look" was to make Hornet program subsystem managers responsible for the key LCC parameters, unit production cost, reliability, and maintainability. Subsystem managers in MCAIR's engineering organization are assigned responsibility for all design requirements in their work breakdown structure (WBS) area of authority, as shown in Figure 4. This responsibility has always encompassed performance, weight and development cost. For the Hornet program, production cost and R and M were added as requirements to be controlled just like weight and performance.

Allocations of the F/A-18 requirements in these areas were made at the subsystem level in order to provide delegation of responsibility. Status of these parameters is periodically updated and reviewed by management, with corrective action proposed for subsystems which significantly exceed their allocations.

Emphasis in the remainder of the paper is placed on management techniques for reducing the operating and supporting (O&S) costs of the Hornet program. The key accomplishment of this program objective is improved R and M in the F/A-18 design. MCAIR and the U.S. Navy have aggressively pursued these R and M improvements in the management, design and test areas of the Hornet program.

Reliability and Maintainability Guarantees

The Hornet prime contract incorporates reliability and maintainability guarantees for key parameters, all of which will be demonstrated by the prime contractor. In this program, R and M are design requirements, not just goals which in prior programs weren't usually achieved.

Principal reliability guarantees are summarized in Table 3. These are not all of the guarantees, but they illustrate that weapon system level parameters are guaranteed along with subsystems such as the radar and avionics suite. Most of the weapon-system level guarantees are demonstrated at approximately 1200 hours and/or 2500 hours into the flight test program. In addition, a 50 flight program is dedicated to demonstrating reliability in a simulated operational environment.

WBS	SUBSYSTEM	SUBSYSTEM MANAGER	UNIT PRODUCTION COST	RELIABILITY	MAINTAINABILITY	WEIGHT
1000	AIR VEHICLE					
1100	AIRFRAME					
1110	BASIC STRUCTURE					
.01	FORWARD FUSELAGE					
.02	CENTER FUSELAGE					
.03	AFT FUSELAGE					
.04	WING					
.05	EMPENNAGE					
.06	LANDING GEAR					
1120	SECONDARY POWER					
1130	HYDRAULIC					
1140	FLIGHT CONTROL					
1150	ELECTRICAL					
1160	ENVIRONMENTAL CONTROL			ALLOCATIONS		
1170	CREW STATION					
1180	FUEL SYSTEM					
1190	AIRFRAME INTEGRATION					
1205	ENGINE INTEGRATION					
1300	AVIONICS					
1310	COMMUNICATION AND IDENTIFICATION					
1320	NAVIGATION AND FLIGHT AIDS					
.01	INERTIAL NAVIGATION SYSTEM					
1330	FLIGHT CONTROL SYSTEM					
1340	AIRBORNE WEAPONS CONTROL					
.01	RADAR					
1350	CONTROL AND DISPLAY					
1360	ELECTRONIC WARFARE					
1370	MISSION COMPUTER					
1400	ARMAMENT/WEAPONS DELIVERY					

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FIGURE 4. SUBSYSTEM MANAGERS ARE RESPONSIBLE FOR KEY LCC PARAMETERS

TABLE 3. HORNET RELIABILITY GUARANTEES

	GUARANTEE	DEMONSTRATED
AIR VEHICLE MFHBF	3.7 HR	50 CONSECUTIVE 2-HR FLIGHTS
MISSION RELIABILITY	7 MISSION FAILURES	
EQUIPMENT MFHBF	33 EQUIPMENT FAILURES	
RADAR MTBF		MIL-STD-781 TEST
1st PRODUCTION UNIT	60 HR	
50th PRODUCTION UNIT	80 HR	
125th PRODUCTION UNIT	100 HR	
AVIONICS MTBF	30 HR	1 YEAR AFTER FSE

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Key maintainability parameters are also guaranteed on the Hornet. Principal parameters are summarized in Table 4; again this is not the complete list of M guarantees. The aircraft-level guarantees will be demonstrated at fleet supportability evaluation (FSE) after approximately 25,000 flight hours have been accumulated. This demonstration will occur in a U.S. Navy environment with Navy maintenance men. The equipment replacement time and fault isolate time demonstrations will occur as part of the maintenance engineering inspection (MEI). Operational Readiness will also be demonstrated during the FSE flight program on fleet aircraft.

TABLE 4. HORNET MAINTAINABILITY GUARANTEES

	GUARANTEE	DEMONSTRATED
DIRECT MMH/FH	11	FSE
MEAN TIME TO REPAIR	1.78 HR	FSE
TURNAROUND TIME	15 MIN	FSE
MEAN TIME BETWEEN MAINTENANCE	0.49 HR	FSE
FAULT ISOLATE TIME	1.75 HR	MEI
ENGINE REPLACEMENT	21 MIN	MEI
RADAR REPLACEMENT	20 MIN	MEI
OPERATIONAL READINESS	85%	FSE

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These R and M guarantees have been taken very seriously by the prime contractor and major subcontractors. Top-level numbers have been allocated to subsystems and major equipment items. All subcontracts contain R and M guarantees based on reasonable allocations of the prime contract guarantees. Also, major subcontracts contain specific R and M demonstration programs.

Designing for Improved R and M

The key to lower LCC and improved availability of the Hornet is the "New Look" emphasis on "Big R" and "Easy M." The Hornet is designed to capitalize on the state-of-the-art in design technology in these areas. Only the highlights of these design features can be presented in this paper. However, both the U.S. Navy and MCAIR understand that the most effective tool for lowering LCC is improving the fundamental reliability and maintainability of the Hornet design.

The Hornet is expected to achieve a reliability in the fleet about three times better than the currently operational F-4J and A-7E, as shown in Figure 5. The Hornet fleet performance expectation is based on a requirement to demonstrate a guaranteed MFHBF of 3.7 hours during FSD.

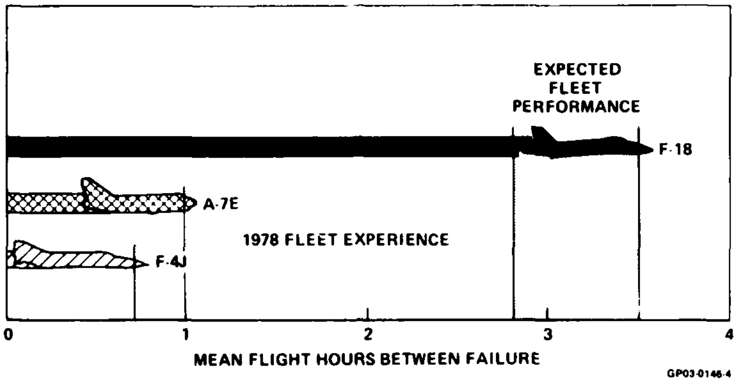

FIGURE 5. F-18 EXPECTED RELIABILITY IS 3 TIMES BETTER THAN FLEET AVERAGE

Some of the Hornet design features to enhance reliability are summarized in Figure 6. Much of the Hornet avionics is solid-state, thus providing low heat generation. Nevertheless, heat is one of the primary contributors to avionics failures and we have emphasized better cooling in the design. The APG-65 radar has been significantly simplified from the F-4J radar through digital processing and extensive use of solid-state circuits. Also, an electric antenna drive is used in the APG-65 instead of a hydraulic drive. It has 8000 fewer parts than the F-4J radar, all of them expected to be more reliable. Although in the same general thrust class, the F404 engine has fewer compressor and turbine stages than the J79 engine in the F-4. A major improvement has been transfer of the engine accessories to an airframe mounted accessory drive (AMAD). Also, the F404 fuel controls are much simpler than those of the J79. Most of the pilot's flight and weapon system information is displayed on versatile CRT displays instead of individual electro-mechanical instruments.

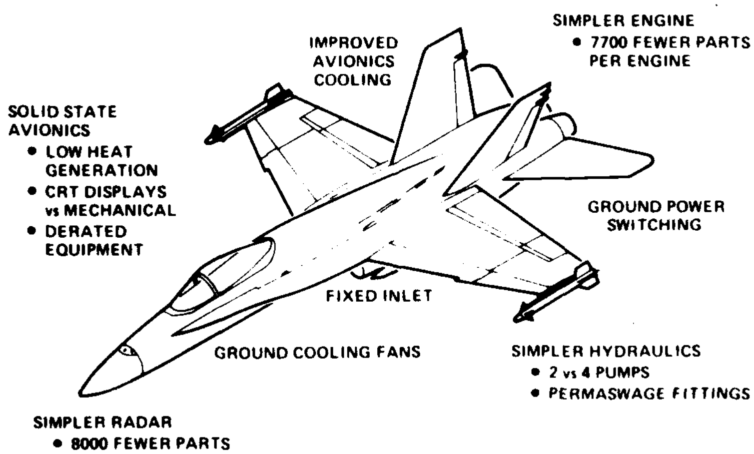

FIGURE 6. IMPROVED RELIABILITY THROUGH DESIGN
F-18 Compared to F-4J

The F404 engine, manufactured by General Electric, contributes to the Hornet's reduced LCC through its design simplicity and ease of maintenance. It has two-thirds the parts of the J79 engine and produces about the same thrust. Also, it is built in modules for ease of maintenance and can be borescoped without removal from the aircraft. The F404 features which contribute to a predicted reliability four times better than the J79 are summarized in Figure 7.

The Hornet's maintainability index, measured in maintenance manhours per flight hour (MMH/FH), shows substantial reduction over current operational aircraft, as depicted in Figure 8. A threshold of no more than 18 MMH/FH, as reported in the Navy's 3M reporting system, was established as an F-18 program requirement. In order to ensure achievement of this operational value, the prime contractor is designing to a requirement of 11 MMH/FH for all direct and Support General design-related maintenance categories. This requirement is based on certain measurement criteria which will equate to about 18 MMH/FH in the 3M system.

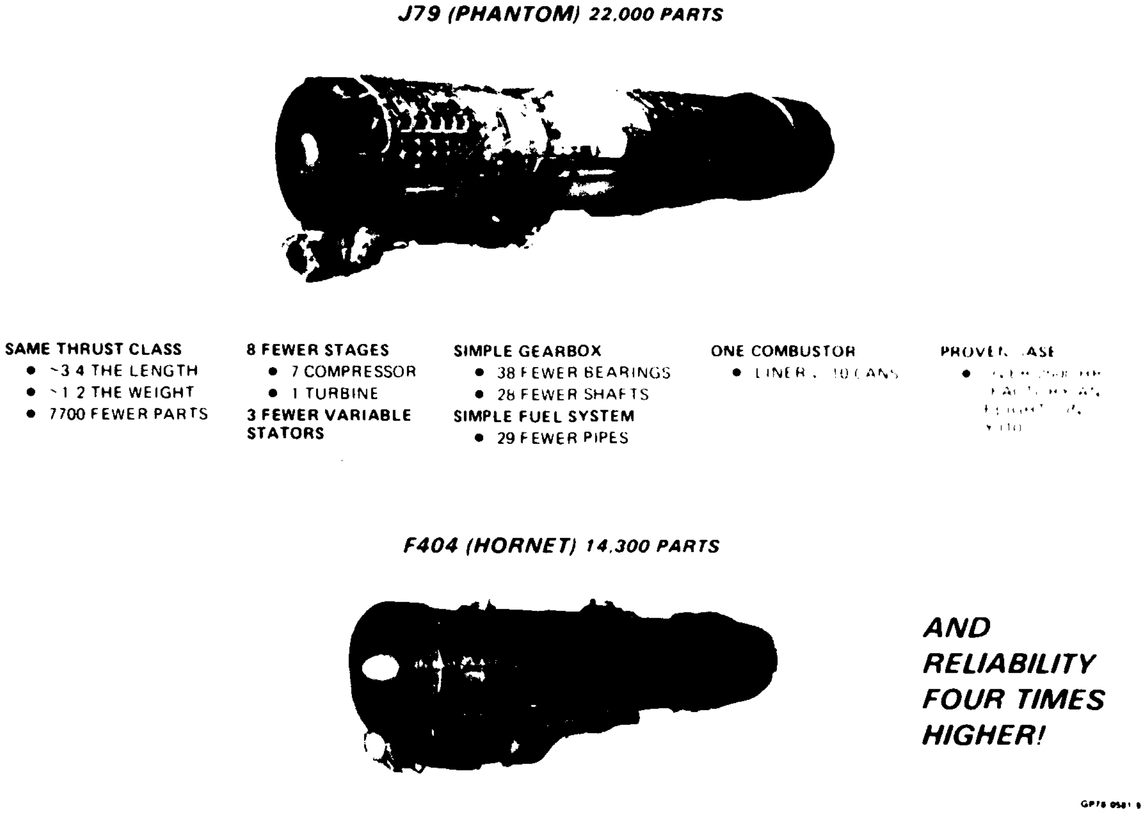

FIGURE 7. ENGINE DESIGN SIMPLICITY FOR HIGH RELIABILITY

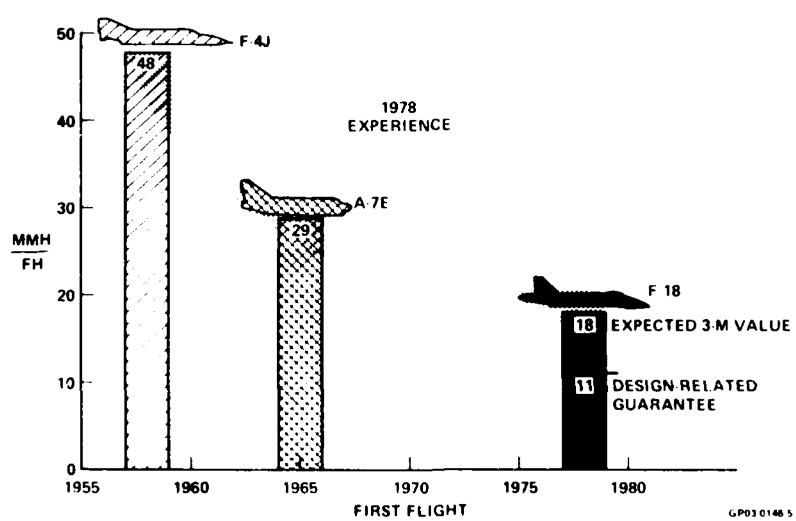

FIGURE 8. F-18 CONTINUES THE TREND TO LOWER MAINTENANCE REQUIREMENTS

A key contribution to reduced maintenance requirements is quick and easy access to all equipment which requires other than rare attention. The Hornet's access provisions are shown in Figure 9. Even engines can be changed in 21 minutes because of rapid access and quick-disconnect features. An auxiliary power unit (APU) provides power for quick systems checkout and self-start. Ground cooling fans also reduce the need for cooling carts during maintenance and pre/post flight checks. Most major equipment has built-in test (BIT) and fault isolate test (FIT) to greatly reduce troubleshooting time.

Failures of most avionics equipment and many of the hydro-mechanical subsystems are indicated in the cockpit and also displayed on a digital display panel in the nose wheel well. The maintenance monitor panel allows maintenance personnel to isolate a failure to a weapon replaceable assembly. Also, consumables status of engine oil, AMAD oil, APU oil, hydraulic fluid, radar liquid coolant, LOX, and fire extinguisher is displayed on this indicator when interrogated by depressing a switch on the panel. A maintenance signal data recorder set is also used to help trouble-shoot systems, including recording the outputs of the engine in-flight condition monitor system (EICMS)

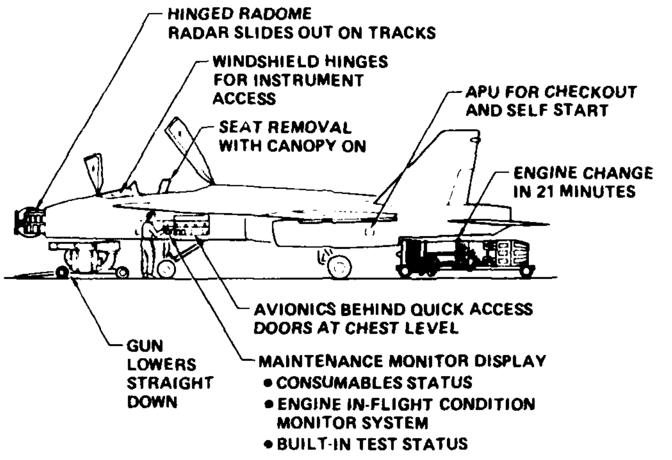

FIGURE 9. DESIGNED FOR EASY ACCESS

Other major maintenance features of the Hornet design are summarized in Table 5. Significant advances have been made in the state-of-the-art in corrosion control on this airplane. Another major improvement in the Hornet design is in the area of fasteners. Not only have the numbers and types of fasteners been significantly reduced from the F-4 to the F-18, but the screw strength has more than tripled. This strength increase, coupled with a better screw head design, should drastically cut the incidences of screw shearing due to overtorqueing.

TABLE 5. HORNET MAINTAINABILITY FEATURES

- BUILT-IN TEST FOR MOST AVIONICS AND HYDRO-MECHANICAL EQUIPMENT
- RAPID FAULT ISOLATION
- CORROSION RESISTANT MATERIALS - COMPOSITES AND 7050 ALUMINUM
- RAPID WRA REPLACEMENT
- SCHEDULED MAINTENANCE MINIMIZED
- NO TURNAROUND OR DAILY GSE

Reliability and maintainability have been considered in all design decisions. Achieving R and M guarantees requires attention to detail. Only the highlights of these Hornet design details have been presented here. Later in this paper, Hornet program management features designed to ensure improved R and M will be described. However, we are constantly aware that any R and M potential benefits must be reflected in the F-18 design in order to be effective.

Operational Mission Environment

A major factor in reducing Hornet O&S costs is the expected improved reliability of F-18 equipment. A key program initiative which promises to contribute significantly to achieving these equipment reliability improvements is implementation of a realistic operational mission environment (OME) as design and test requirements. Traditional design and test requirements often have been found to be inadequate in representing fleet operating stresses. As a result, the real-world operating environment contributes to failure modes that were not considered during design, nor discovered and corrected during demonstration tests. To solve this problem, the U.S. Navy and MCAIR defined realistic training and combat mission profiles as the basis for a detailed expected operating environment of the airplane. A comprehensive analysis of the Hornet flight, ground operating, storage, and maintenance handling environment was then used to tailor procurement specifications for design and test requirements of major systems.

As the first step in the OME process, outlined in Figure 10, twelve training missions were defined based on training syllabus requirements, squadron surveys, and pilot experience. Six critical combat missions were based on the Hornet's Operational Requirement. A frequency of occurrence for each mission was established for Navy Fighter, Navy Light Attack, and Marine Fighter/Attack squadrons, as well as ship shore and combat/training sortie ratios. The Hornet OME builds on the foundation of the mission environments, based on mission profiles, but also includes combat maneuvers, occasional transient excursions beyond the design flight envelope, ground operation, and handling and storage conditions. This comprehensive OME definition forms the basis for establishing expected flight loads, vibration, temperature, altitude, humidity, acoustics, salt, and dust design-to requirements. Critical design points from the OME become design-to requirements for all Hornet equipment. Thus, design and test conditions tailored to the expected environment of this equipment were derived and were imposed in the procurement specifications, replacing testing to less severe conditions of classical military specifications.

Accelerated testing approaches were developed to time-compress the design life testing for test span reductions and cost economies. Addition of temperature cycling, random and sinusoidal vibration, and humidity are the major changes from the MIL-STD-781B test specifications for most equipment. For certain critical mission equipment, such as the APG-65 radar, temperature, humidity, and vibration cycling are combined. A comparison of OME and MIL-STD-781B testing requirements for avionics equipment is presented in Table 6.

A key part of the F-18's "New Look" approach to designing to reduced life cycle cost is an integrated test program. This test program emphasizes two separate phases, development and demonstration tests. The expected improvement in equipment reliability during these test phases is illustrated in Figure 11.

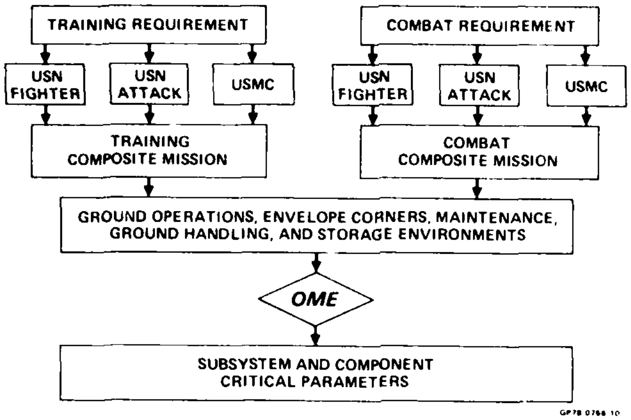

FIGURE 10. OPERATIONAL MISSION ENVIRONMENT DEVELOPMENT

TABLE 6. MAJOR AVIONICS TESTING CHANGES WITH OME

PARAMETER	BASELINE MIL-STD-781B	OME
– **TEMP EXTREMES**		
CHAMBER	54° TO +71°C	54° TO +85°C
COOLING AIR	54° TO +49°C	54° TO +63°C
– **TEMP SHOCK**		
COOLING AIR	5°C/MINUTE	33°C/MINUTE
– **VIBRATION**		
TYPE	FIXED SINE	RANDOM + FIXED SINE
INTENSITY	±2.2 g	MAX PERFORMANCE
– **HUMIDITY**	NONE	TYPICAL MISSION
– **ALTITUDE**	SEA LEVEL	SEA LEVEL TO 15,250 m

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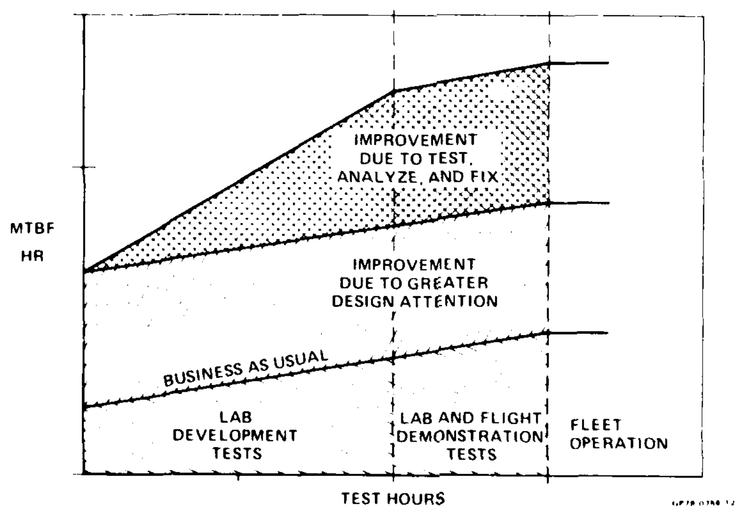

FIGURE 11. RELIABILITY IMPROVEMENT WITH THE "NEW LOOK"

The primary objective of the development phase is early design assessment of mission-critical environments. It emphasizes test, analyze, and fix (TAAF) with closed loop failure reporting. An improvement in initial equipment reliability (at the start of development testing) is expected due to the more realistic OME design conditions. A further improvement in the reliability growth curve slope is predicted because of the improved realism of the OME test environment and the TAAF approach.

The objective of the demonstration phase is the traditional verification of design requirements in laboratory and flight tests. A new requirement in the Hornet program is a 50-flight dedicated reliability demonstration. This test program will simulate the spectrum of operational mission conditions, including realistic equipment operations. More than 7 mission failures or 33 equipment failures constitutes failure to pass the demonstration.

Trade Studies

Trade studies have traditionally been the key tool in the evolution of a weapon system design. With the increasing emphasis on reducing life cycle cost, a new dimension is added to the designer's classical performance versus weight trade-off process. Most trade studies have usually been the private domain of those engineers intimately involved in the design process. In the Hornet program, added emphasis and visibility was placed on this trade-off process in the following ways:

- Trade studies were conducted in more depth, particularly with respect to reliability, maintainability, and logistics alternatives
- A comprehensive planned operational scenario was established by the U.S. Navy covering such elements as flying hour program, expected operational inventory, site activation schedule, land-based/carrier-based mix, and such cost factors as personnel pay and fuel cost
- Trade studies were documented in greater detail to ensure adequate consideration of inter-disciplinary effects and to facilitate design-to-cost and life cycle cost reporting
- Configuration management was tied to the trade study process since Design Decision Memo's were used to summarize trade study results as well as to document changes to the configuration baseline

Formal trade studies were started much earlier in the Hornet program than on previous programs, being triggered by both U.S. Navy and contractor-suggested alternatives to the design baseline. More than 100 formal trade studies had been started at FSD contract go-ahead and over 700 formal studies had been completed by the end of 1978. Life cycle cost avoidance documented by these trade studies is quantified in Table 7. These cost "savings" are labeled avoidances because the final design had not been established so, technically, these cannot be counted as savings. In other words, if these trade study decisions had not been implemented, the Hornet program LCC would have been 260 million dollars higher than it is today.

TABLE 7. LIFE CYCLE COST AVOIDANCE

NO. OF FORMAL TRADE STUDIES = 400+			
LCC AVOIDANCE	DEVELOPMENT	=	\$ 12 $\bar{M}$
	PRODUCTION	=	\$145 $\bar{M}$
	OPERATING	=	\$103 $\bar{M}$
	LCC	=	\$260 $\bar{M}$

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Some examples of trade studies which emphasized LCC considerations are listed in Table 8. The common wheel and tire trade-off is discussed later in this paper. The wing pylon jettison trade-off was basically whether to jettison the pylon with the tanks and armament racks or retain it with the airplane if it became necessary to jettison external stores. The decision was to retain the pylons due to the cost and weight avoidance. Cost and weight can be avoided because of a simpler pylon design and less complex pylon mounting attachments in the wing. Performance is degraded slightly, of course, in combat or emergency situations because of the additional pylon weight and drag. The flight control system (FCS) simplification study resulted in significant cost and weight reductions by providing minimum essential redundancy through redesign of the computer and some actuators. Hughes Aircraft, the APG-65 radar supplier, found that it would be difficult to achieve its reliability guarantees with a radar designed to fit within the allocated space in the Hornet's nose. A trade study increasing this volume 0.5 ft^3 resulted in a relatively large LCC avoidance, as well as a small weight savings. The radar WRA support trade study evaluated alternatives of VAST, modified VAST, and new-design test equipment to support the radar. The selected new Radar Test Station resulted in almost \$20 million of LCC avoidance.

TABLE 8. EXAMPLE LIFE CYCLE COST TRADES

ITEM	COST SUMMARY: Δ FSD (\$ $\bar{M}$)	Δ UNIT PROD (\$ K)	Δ LIFE CYCLE (\$ $\bar{M}$)	Δ WEIGHT LB/(kg)	PERFORMANCE
COMMON F-18/A-18 WHEEL/TIRE	−0.8	+0.4	−7.5	+89/(+40)	DEGRADED
WING PYLON JETTISON	−2.1	−4.0	−23.8	−40/(−18)	DEGRADED
FCS SIMPLIFICATION	−0.8	−33.0	−33.2	−60/(−27)	IMPROVED
INCREASED RADAR VOLUME	−0.5	−18.4	−31.4	−3/(−1)	NEGLIGIBLE
RADAR WRA SUPPORT	−5.2	N/A	−19.8	0	NO CHANGE

NAVAIR asked MCAIR, in early 1976, to conduct a trade study addressing the issue of whether both the F-18 and A-18 could utilize a common wheel and tire (Table 9). At that time, several hardware differences existed between the F-18 and A-18 including a smaller wheel and tire on the F-18. It was known that installing the larger tire on the fighter would result in a larger cross-sectional area and consequent higher drag. Also, unit cost and weight of the fighter would increase. However, the fighter's brake and tire life would be lengthened because of its lower operating weight. The trade study showed that the Hornet programs' LCC would be reduced by selection of the alternative approach and the larger wheel and tire was selected for both the F-18 and A-18 designs. The details of the O&S cost reduction are shown in Table 10. The major cost savings can be seen to accrue from the elimination of 1370 brake stack replacements throughout the Hornet's life cycle.

TABLE 9. COMMON F-18/A-18 WHEEL/TIRE STUDY

ISSUE	SHOULD FIGHTER AND ATTACK VERSIONS UTILIZE COMMON WHEELS AND TIRES?	
BASELINE	FIGHTER 30 x 9.5 x 14.5 TIRE ATTACK 30 x 11.5 x 14.5 TIRE	MIN REQUIREMENT
RESTRAINT	ATTACK VERSION MUST USE LARGER TIRE/WHEEL	
CONSIDERATIONS	**LARGE TIRE ON FIGHTER** **— DEGRADES PERFORMANCE** **— INCREASES UNIT COST $400** **— ADDS WEIGHT - 89 LB/(40 kg)** **— IMPROVES BRAKE LIFE** **— DECREASES LIFE CYCLE COST**	

COMMON TIRE SELECTED

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TABLE 10. COMMON WHEEL/TIRE LCC ANALYSIS

	COST CHANGE FOR COMMON WHEEL/TIRE $M
FSD	−0.788
PRODUCTION	+0.319

O&S

	DIFFERENT	COMMON	Δ COST
REPLACEMENT TIRES			
FIGHTER	59,888	85,908	(−0.381)
ATTACK	36,910		
REPLACEMENT BRAKES			
FIGHTER	4,104	5,830	(−5.064)
ATTACK	3,096		
OTHER O&S			
LABOR, POL, ETC.			(−1.541)
TOTAL O&S			6.986
TOTAL LCC SAVINGS			$7.455M

LCC in Supplier Selection

Life Cycle Cost evaluations were made of all bidder's proposals in the source selection of major F-18 equipment. The impact of the "New Look" on the equipment procurement process is illustrated in Figure 12. LCC savings are shown relative to supplier selection based on only performance and weight, the traditional selection basis. A small savings would accrue if the supplier selection would have been based strictly on a DTC bias to the lowest unit production cost. Larger savings result if the suppliers would have been selected on the basis of best R̲ and best M̲. The largest savings occur if the supplier expected to provide the lowest life cycle cost was selected.

The actual supplier selected, for those major equipments considered in this evaluation, was judged to provide the lowest LCC in all cases but one, and in this case the supplier was rated second in LCC. For these major equipment items, LCC savings of about $90 million were realized by conscientiously considering all of the elements of the "New Look" in LCC control in the procurement process.

Operating and Support Costs Comparisons

The Hornet is designed to replace the F-4 and A-7 in the fleet, so it is appropriate to compare these systems in an O&S cost scenario to demonstrate that this new system will not cost more to operate than the airplanes it replaces. The data presented in this comparison are taken from the 1979 Navy resources model (NARM). It is the U.S. Navy's best estimate of the cost to operate and support operational systems or projected new systems, such as the Hornet.

A key input to any O&S cost comparison is the number of maintenance people required in a twelve-plane squadron. A comparison of this factor in Figure 13 shows that a Hornet squadron is projected to require between 24 and 34 fewer enlisted people than an F-4J or A-7E squadron, primarily due to its greatly improved reliability and maintainability. The reduced officer requirements of the Hornet and A-7E, from the F-4J, reflects the one-place designs.

Projected O&S cost savings from introduction of the Hornet are depicted in Figure 14. For this comparison, F-4J and A-7E operating costs from the 1979 NARM are used to construct a fictional flying hour program (2.62 $\bar{M}$ flight hours) equal to the Hornet 20-year program.

As compared to a force of F-4J aircraft, the contributions of squadron manning and fuel to O&S cost reductions are seen to be about equal. The depot rework, repair material, and replenishment spares contribute a somewhat lesser amount; the much lower frequency of material replacement is somewhat counter-balanced by the higher costs of F-18 material and spares.

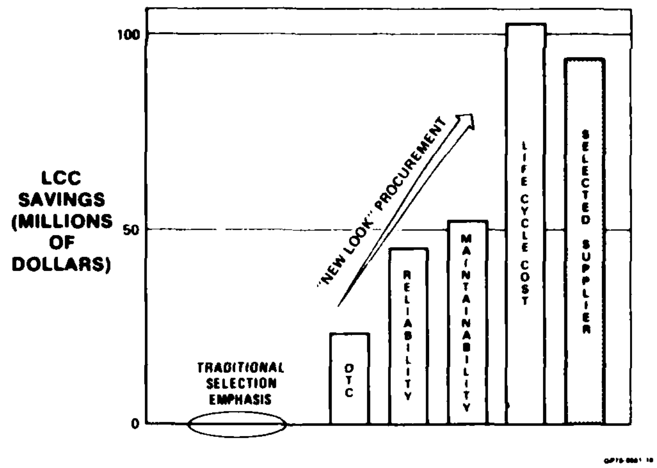

FIGURE 12. F-18 PROCUREMENT RECORD - LCC SUCCESS
Based on 46% of Procured CFE Cost

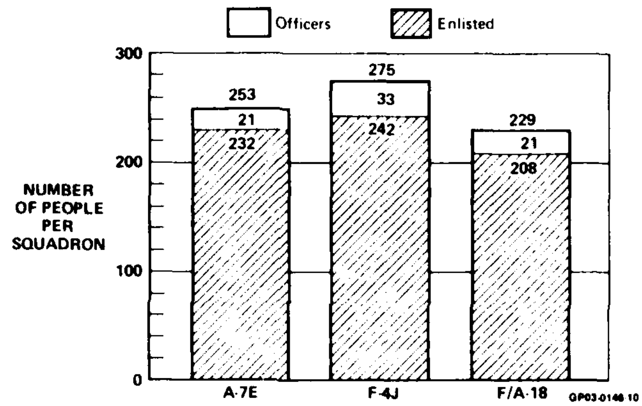

FIGURE 13. HORNET REQUIRES FEWER MAINTENANCE PEOPLE

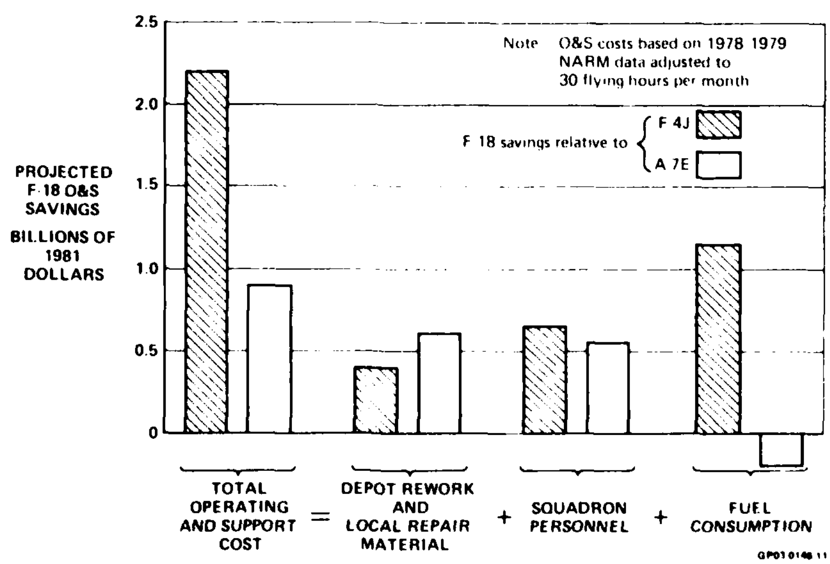

FIGURE 14. HORNET PROMISES TO SAVE OPERATING AND SUPPORT COSTS

The O&S cost savings from A-7E replacement by the Hornet are less dramatic, although still significant. The leading contributor to these savings is again maintenance personnel. The A-7E consumes slightly less fuel than the Hornet. Depot rework and the material categories contribute the remainder of the O&S cost savings.

These O&S cost comparisons illustrate that introduction of the Hornet will reduce the Navy's operating cost budget, when F-4Js and A-7Es are replaced. It should be noted that the NARM report uses Hornet inputs that are somewhat more conservative than the requirements imposed on the contractor.

Lessons Learned

The purpose of the Hornet design to life cycle cost emphasis is not to accurately predict the F-18's actual LCC many years in the future. Rather, this emphasis has served to prioritize design and management actions to ensure the lowest practicable life cycle cost. We have specifically emphasized the elements of cost which can be significantly reduced by design action during FSD. Both the U.S. Navy and contractors involved in the Hornet program have learned much about the challenges of designing to life cycle cost. Some of our "Lessons Learned" are summarized in Table 11.

TABLE 11. LCC LESSONS LEARNED

- **ESTABLISH REALISTIC DESIGN-TO REQUIREMENTS**
  GUARANTEE AND DEMONSTRATE WHERE POSSIBLE
- **USE INCENTIVES WISELY**
  PASS DOWN TO EQUIPMENT SUPPLIERS
- **USE OME TO DESIGN AND TEST EQUIPMENT**
- **ESTABLISH DESIGN-CENTERED, MULTIDISCIPLINED COST ANALYSIS TEAM**
- **TAKE TRADE STUDIES SERIOUSLY**
- **CONSIDER LCC IN MAJOR PROCUREMENT DECISIONS**
- **CONDUCT RIGOROUS MULTIDISCIPLINED DESIGN REVIEWS**

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We have learned that designing to life cycle cost is not greatly different from designing to any other technical parameter. It is essential that the designer have a "design-to" allocation presented in an understandable form; in terms of unit production cost and key design-sensitive R̲ and M̲ parameters. Allocations should be challenging, but not unreasonable. Whenever possible, these requirements should be stated as guarantees with specific demonstrations of the guaranteed values specified in the contract.

Prime contracts, as well as major subcontracts, should contain monetary incentives based on the contractor's control of the LCC drivers. Where possible, these incentives should be based on specific achievements and demonstration of guarantees.

Designing and testing to an operational mission environment is one of the key technical innovations of the F-18 program. The OME emphasis, tied to a test, analyze and fix philosophy, will undoubtedly do more to improve the basic equipment reliability and reduce Hornet O&S costs than any other action taken in the program.

It is impossible for a "cultist" group of analysts to set up shop remote from the design action and have any meaningful impact on the evolving design. An effective, multidisciplined LCC analysis team, consisting of specialists in cost analysis, reliability, maintainability, and ILS must work hand-in-hand with the project design team. It is especially important that high-confidence methods of prediction for all LCC elements be utilized, giving everyone confidence that cost analysis answers truly represent the impact of design changes.

Trade studies have traditionally been the heart of the iterative design optimization process. In the Hornet program, the trade study process has been expanded to encompass all elements of LCC and ensure that all specialists are heard before a design decision is made. In addition, documentation has been strengthened to provide traceability and auditing of the design process.

A cost effective procurement process is essential to the success of a design-to-LCC program. More than 50% of the Hornet's cost (and also its reliability and maintainability) is contributed by subcontractor's hardware. Therefore, procurement policy must put teeth into source selection by emphasizing these LCC elements in the source selection process. Equipment suppliers must be convinced that the customer, both the prime contractor and the using service, place highest priorities on R̲, M̲, and LCC.

Finally, thorough design reviews must be conducted by qualified program management teams to ensure that all elements of LCC are being balanced in the evolving design.

Designing to life cycle cost is a way of life in today's budget-limited weapon system procurement environment. This design philosophy requires some changes in the historic design process, industry definitely cannot continue "business-as-usual." However, the technology and management disciplines to effectively accomplish the new DTC objectives are in hand. The Hornet program is demonstrating that designing to life cycle cost can be effectively accomplished

DESIGN TO COST
AND
THE F-16 MULTIROLE FIGHTER

by

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SUMMARY

The low cost of the F-16 Fighter Aircraft is the result of a selected balance of innovative new technologies, available low cost material and equipment, and cost reducing configuration options. This has been implemented through the application of design to cost concepts from the beginning of the program.

The F-16 Full Scale Development contract contained several clauses which provided downstream cost control including control of both acquisition and operations. Response to these contract requirements resulted in an acquisition cost control plan which was based on the allocation of target costs to fourth and fifth level WBS elements, periodic production cost estimates, feedback to WBS Element Managers, immediate corrective action as required, and monthly and quarterly status reports. A key part of this plan was the identification and close tracking of a few cost drivers which comprise over 50 percent of the air vehicle cost.

A number of specific contract provisions, as noted above, are aimed at control of operating and support costs. These provisions provide financial incentives and penalties for consideration of reliability and other logistic support parameters. Other control provisions require cost considerations in trade studies, engineering change proposals and in vendor selections.

In summary, the F-16 program includes a wide variety of live cycle cost control measures concentrating on principal cost drivers.

PREFACE

Low cost has been a criterion of the F-16 program from the beginning. As early as 1968, the idea of a small, lightweight fighter emerged from discussions of studies by the United States Air Force and General Dynamics Corporation. The principal issue of that situation is illustrated by the following questions which were being asked at that time:

> "Can a lightweight fighter have superior maneuvering performance and still have adequate range and combat fuel allowance?"
>
> "If it can, at approximately one-half the weight (of then current fighter trends), can it indeed be built for one-half the cost or less?"

Subsequent studies by both the USAF and General Dynamics indicated that the answer to both questions was yes. These studies resulted in the definition of a viable lightweight fighter in the 30,000 to 35,000 pound takeoff gross weight class. Concurrent cost estimates indicated that this fighter could be produced for a unit average flyaway cost of approximately $3 million.

In 1971, the USAF issued a request for proposal for a lightweight fighter aircraft. The contract required the design, development and fabrication of two prototype aircraft. Other requirements of the contract were

- Assess and certify aircraft safety-of-flight.
- Conduct a joint Contractor/Air Force flight test program.
- Train Air Force test pilots.
- Provide total contractor support during the flight test program.

- o Provide a data accession list.

- o Prepare a final report.

Cost appeared as an important requirement. First the prototype development program cost commitment by the Air Force to General Dynamics for two prototype aircraft including one year of flight test, could not exceed $37.9 million. Second, a production cost goal was specified as the average unit flyaway cost for 300 aircraft of $3 million in FY-72 dollars.

Both the Air Force and General Dynamics realized that "business-as-usual" would not produce the desired results, i.e., lightweight, high performance, low cost. Therefore, the basic approach taken in establishing contract requirements departed from the customary. Notably, complete latitude was provided the contractor in making trades. It was required only that General Dynamics "Design, develop and fabricate two prototype aircraft substantially in accordance with Contractor Technical Management and Cost Proposal FZP-1401, dated 18 February 1972". Furthermore, there were no contractually obligated Statements of Work or detail specification requirements; in a competitive environment for both performance and cost, design responsibility rested solely with the Contractor.

General Dynamics believes that this far sighted innovative approach by the USAF provided the solid foundation on which the F-16 program was successfully built.

In 1974, following the prototype program, the USAF issued a request for proposal for the Full Scale Development (FSD) of an Air Combat Fighter. The contract was awarded in early 1975. Numerous clauses in this contract continued or perhaps increased the emphasis on cost. Included now were cost control measures related to operation and support (O&S) of the aircraft. For the first time, at least in the F-16 Program, comprehensive contract clauses placed cost control requirements on all phases of the life cycle of an aircraft, i.e., development, acquisition and operation/support.

Development cost control was achieved simply by the austere limitation by the government of the amount of funding available and a fixed price contract in which the contractor was required to share in cost overruns.

Acquisition cost control was achieved contractually by

1. Specifying a unit production cost goal.

2. Providing award fees for conducting cost reduction trade studies.

3. Establishing a 70/30 sharing of any contract overruns or underruns.

4. Scheduling specific design-to-cost milestone events.

Operation/support cost control contract clauses included

1. The control of operation and support costs as a management objective.

2. Award fees for conducting O&S cost reduction trade studies.

3. Award fees for achieving "Logistic Support Cost Targets".

4. Reliability Improvement Warranty guarantees on selected equipments.

5. Guarantees for Target Logistic Support Costs for selected equipments.

In a Design to Cost Symposium such as this, these contract clauses devoted to cost control deserve a more detailed examination. But first, let us look at the program phase during which it might be stated that the "die was cast" with regard to establishing the cost of the F-16 Aircraft. This phase was the Prototype Development of the YF-16.

1. PROTOTYPE DEVELOPMENT - DTC EMPHASIS

The YF-16 Prototype Development Program, in addition to the objectives previously discussed, i.e., lightweight, high performance, low cost, included the following specific major objectives:

1. To fully explore the advantages of emerging technology and,

2. To reduce the risk and uncertainties of full-scale development and production.

These objectives present a special challenge to the airplane designer in that they appear to represent a diversity of purpose, i.e., advance technologies tend to increase risk and uncertainty. In view of this, careful attention was given to the selection of new technologies. The criteria for selection were established as follows:

1. Must contribute directly to the performance/design goals.

2. Must be sufficiently advanced to warrant prototyping.

3. Must individually not be of such high risk as to jeopardize the total program.

4. Must fall within imposed constraints of cost, complexity, and utility.

To counterbalance the potential cost increase of the advanced technologies, certain principles were adopted to minimize costs:

1. Emphasize the new and novel technology features of the design that are significant in meeting performance goals. Where new technology is not required, use proven systems and components wherever possible, particularly where only marginal benefits will accrue by redesign.

2. Establish specific cost goals and be willing to compromise or trade performance or operational capability to meet them.

3. Design for low manufacturing cost by making detail and component assemblies simple to manufacture, using low cost materials and processes, standardizing hardware and designing for multiple-use parts and assemblies.

The advanced technologies and design features selected for the YF-16 Prototype airplane, illustrated in Figure 1, included:

- o Variable camber wing
- o Wind-body blending
- o Vortex lift
- o Relaxed static stability/fly-by-wire
- o Bottom inlet location
- o Composite materials
- o "Hi-G" seat-back angle
- o Side-stick controller
- o Clear view-forward canopy with 360 degree vision

Those features which contributed significantly to cost reduction included:

- o Single existing engine
- o Normal-shock fixed inlet
- o System simplification
- o Multiple-part useage
- o Standardization
- o Materials selection.

This very limited discussion of the YF-16 Prototype Program was presented to illustrate the point that cost had indeed achieved a status co-equal to that of performance as a design parameter. For those who may wish to pursue design-to-cost and the YF-16 Prototype Fighter in more detail, please refer to item number 1 in the List of References. The related discussions in this paper have borrowed extensively from this source.

As noted previously, a production cost goal was specified in conjunction with the Prototype Program. This goal was $3 million, in FY-72 dollars, average unit flyaway cost based on a 300 airplane production program. Based on the YF-16 design and fabrication

of two aircraft, a production cost assessment was made resulting in an estimated cost well within the goal, thus further substantiating the belief that a high performance, lightweight fighter could be built for $3 million.

2. FULL SCALE DEVELOPMENT - DTC/LCC ASPECTS

The YF-16 Prototype airplane provided a sound base from which to move into the full scale development of a production version. In fact, the prototype design approach was to design initially an operational aircraft and then adapt it to the constraints of funding and program objectives of the prototype contract. In addition, the prototype design philosophy included consideration of the potential for the aircraft to be ultimately put into production. Again cost was a major driver as illustrated in Figure 2 and 3. These design features were integrated into the configurat ı primarily to improve manufacturing efficiency and reduce cost.

1. Multiple-Usage of Parts - many parts were made interchangeable left and right, i.e., flaperons, horizontal tails, leading edge flap actuators, main landing parts.

2. Use of equipment components already developed.

3. Standardized fasteners, limited to the number of types.

4. Limited material types - primary material is low cost aluminum.

5. Modular design airframe.

With a sound production design well defined in considerable detail and a production unit cost estimated to be well within the objective, the challenge then became one of controlling the costs during development and manufacture. Awareness of this resulted in the USAF incorporating into the F-16 Full Scale Development contract a number of clauses directed toward this end. These clauses can be categorized into those related to acquisition cost control and those related to operation/support (O/S) cost control. These clauses are listed as follows:

Acquisition Cost Control

1. Specifying an average unit production flyaway cost goal.

2. Award fees for conducting air vehicle trade studies.

3. DTC schedule milestones.

4. 70/30 cost sharing of over or under-runs.

Operation/Support Cost Control

1. Management objective to control O/S costs.

2. Award fees for conducting O/S cost reduction trade studies.

3. Award fees for achieving Logistic Support Cost Targets.

4. Reliability Improvement Warranties (RIW) on selected components.

5. Target Logistic Support cost guarantees on selected components.

These contract requirements and General Dynamics response to them provided the basis for acquisition and O/S cost control which continues to be effective even today. It would seem worthwhile, then, to examine these contract requirements in some detail.

3. ACQUISITION COST CONTROL

One of the effective cost controls as the program moved into the development/production phase was establishing a unit cost limit on the production vehicle. In the case of the F-16 this is stated as a unit production flyaway cost goal of $3,842,525 dollars. The basis for this is the cumulative average cost for 1000 airplanes at the rate of 15 per month in FY 1975 dollars.

This cost goal was divided into two areas of responsibility, i.e., the United States Government is responsible for the Engine, the Radar and certain Government Furnished Aircraft Equipment items (GFAE); General Dynamics is responsible for the remainder. This resulted in a General Dynamics cost goal of $2,323,074 dollars. The contract further

required that "the contractor demonstrate the extent to which the airframe manufacturers portion of the cumulative average unit production flyaway production costs for 1000 production aircraft at a maximum rate of 15 per month will meet a goal of $2,323,074 dollars or less expressed in FY 75 dollars". The contract required two formal demonstrations, 19 months and 25 months after contract award. To put this in perspective with regard to schedule; the first demonstration was one month after completion of the Critical Design Review (CDR) and the second was three months after the Production Readiness Review.

General Dynamics plan for meeting this production cost goal consisted of the following:

1. Setting unit production cost goal at the 4th level Work Breakdown Structure (WBS).

2. Periodic cost estimates.

3. Assigning the responsibility for meeting these goals to WBS Element Managers.

4. Identification of cost drivers with special emphasis on cost control.

The process for implementing this plan is illustrated in Figure 4. DTC targets at the 4th level WBS were assigned shortly after contract award. Each WBS target cost was further allocated as to functional department. Periodically, cost estimates were made and compared to the targets. Any overrun would cause corrective action to be initiated by the affected Element Manager. In addition to the WBS tracking, cost drivers were identified and tracked on a more frequent basis. Cost analyses of the entire air vehicle indicated that fifty (50) items comprised approximately eight-two percent (82%) of the total cost target. This permitted an efficient expenditure of manhours for the purpose of cost control.

The assignment of cost targets to the 4th level WBS resulted in the target being the responsibility of a single individual. This individual is the WBS Element Manager who, in most cases was also the responsible design group supervisor. The relationship of these individuals to top management is illustrated in Figure 5. Each Element Manager reports directly to the Program Director. This provides him immediate access to the top decision making function in the program.

As noted above, most Element Managers are also design supervisors who have normal design responsibilities. They also have the responsibility in their WBS for the reporting of status, integration and review of information pertaining to all functional departmental assigned responsibilities within their WBS.

For example, in Design To Cost targets, an Element Manager is assigned a target containing costs broken out by Engineering, Tooling, Manufacturing, Quality Assurance and Procurement. Figure 6 illustrates this breakout at several levels of WBS. The Element Manager is responsible to the Program Director for monitoring and reporting on the periodic cost estimates for his WBS. Any overrun situation and corrective action, if any, is discussed and agreed to by these two individuals. Sometimes a cost overrun in one WBS could be compensated for in an underrun in another WBS; in these instances, the Program Director might elect to take no action as long as, in his judgment, the total cost target was being met. It is considered very important to maintain this management option; otherwise in some instances an unwarranted amount of time and effort could be expended to correct a relative small cost overrun.

To further help the Element Manager in cost control, an analysis was made to determine whether a few high cost items might bear special attention. As noted above, it was determined that 50 cost drivers accounted for eighty-two percent (82%) of the cost target. This is illustrated in Figure 7. These drivers, it turns out, are spread rather evenly among the major divisions of the air vehicle, i.e.,

AIR VEHICLE ELEMENT	NUMBER OF COST DRIVERS
Airframe	22
Flight Control	9
Avionics	11
Armament	2
Weapons Delivery	6

Some examples of cost drivers are:

- o Nose Radome
- o Landing Gear
- o ECS Heat Exchanger
- o Flight Control Computer
- o Inertial Navigation Set
- o Fire Control Computer
- o Radar E/O Display

Cost estimates of cost drivers were provided to the Element Manager more frequently than for the complete WBS element. This proved to be effective as well as efficient.

Another major acquisition cost control effort involved trade studies. Trades were utilized effectively since early in the program. During FSD/Production design, they continued to be productive.

A total of 397 air vehicle trade studies in all major areas were accomplished as illustrated in Figure 8. The total potential value of all trades was $117,789,900. The value of those trades actually implemented was $88,731,900 total or $136,512 per aircraft. This represented approximately 5% of the DTC target. Figure 9 illustrates a typical structural type trade.

As noted previously, the contract provided for an award fee of up to $800,000 for the successful accomplishment of the air vehicle trade studies.

In addition to the above, DTC/LCC analyses of supplier proposals were used extensively in making procurement decisions. A detailed life cycle cost analyses was prepared on selected major procurement cost items.

4. OPERATION AND SUPPORT COST CONTROL

Control of operation and support costs is perhaps more difficult than acquisition costs. For one thing, O&S costs are incurred in a time period much later than production costs. Another problem is that O&S costs are generated by a variety of organizations, groups, and agencies, whereas, production costs generally are under the control of a single prime contractor.

This points up the problem then of a prime contractor attempting to control downstream operation and support costs. However, in spite of the difficulties there are some O&S costs that the prime contractor can influence.

Two of the most powerful O&S cost drivers that can be controlled by the prime contractor are air vehicle reliability and maintainability. General Dynamics proposed and implemented a number of design features which will result in reduced O&S costs including:

- o Improved engine removal.
- o Improved maintenance access.
- o Built-in performance indicators.
- o Extensive use of existing hardware.

Also during design special attention was given to

- o Fuel containment.
- o Protection against water in electronic equipment.
- o Corrosion prevention.
- o Proven electrical connectors.
- o Minimization of design features which contribute to stress corrosion.
- o Maintaining a good margin for cooling of electronic equipment.

- o Requiring minimizing of piece-part count in complex electronic equipment.
- o Selection of materials which are resistive to aging.

With these design features and managements emphasis on cost control, General Dynamics accepted the contractual requirements for Reliability Improvement Warranty (RIW) and Target Logistic Support Cost Guarantees.

In the case of RIW, the contract required the contractor to provide (at firm fixed prices)

- o a 48-month (or 300,000 flight hour) reliability improvement warranty on any or all of the First Line Units (FLUs) listed below, or
- o a 48-month (or 300,000 flight hour) reliability improvement warranty with MTBF guarantee on any or all of the following FLUs:

1. Flight Control Computer (*)
2. Inertial Navigation Unit (*)
3. Fire Control Computer
4. Radar E-O Display
5. Radar E-O Signal Generator Electronic Unit
6. Head Up Display (*)
7. Head Up Display Electronic Unit (**)
8. Radar Antenna (*)
9. Radar Transmitter (**)
10. Radar Digital Processor (*)
11. Radar Computer (*)
12. Radar Low Power RF (*)

The contract provides that the government must exercise this option on or before the production decision date and prior to spares provisioning. The terms of the warranty are that General Dynamics must deliver all selected option FLU's, during the term of the warranty period free from defects in design, material; and workmanship and shall operate, when required, in its intended environment in accordance with contractual specifications. The items identified by (*) were selected for RIW. Those identified by (**) were selected for RIW-MTBF.

5. LOGISTIC SUPPORT COST

This contractual provision involves two types of logistic support cost commitment, i.e.,

- o Target Logistic Support Cost - Correction of Deficiency (TLSC - COD).
- o Target Logistic Support Cost - System (TLSC - SYSTEM).

For the TLSC-COD, General Dynamics guarantees that, for the selected FLUs (to be selected from the list above) the measured Logistic Support Cost (MLSC-COD) will not exceed a specified total TLSC-COD value. The MLSC-COD is to be determined by an equation provided by the Air Force in the original contract. Certain parameters of the equation would be measured during the verification test specified in the contract. This test is to last for a period of 3500 flying hours and begin six months after the first F-16 squadron becomes operational. If the total MLSC-COD exceeds the total TLSC-COD by more than 25%, General Dynamics must institute a correction of deficiencies course of action which will bring the logistics cost within the prescribed range.

The contract, in addition to providing the above methods of O&S cost control, also contains provisions for related award fees, i.e., TLSC and Supportability Trade Studies.

Award Fees are provided for in the contract for both TLSC-COD and TLSC-SYSTEM. The potential fees are $2 million for TLSC-COD and $6.4 million for TLSC-SYSTEM. The contractor

is eligible for the awards if the respective MLSC does not exceed the TLSC. The final determination is to be made by the government.

The contract also provides for an award fee related to supportability trade studies. The potential of this fee was $2.4 million.

A total of 64 supportability trade studies were accomplished in many areas as illustrated in Figure 10. The total potential value of all trades was $964 million. The value of all trades actually implemented was $563 million. This represented approximately 14% of the total life cycle cost of the basic F-16 program.

The above discussions on logistics costs control have been brief to fit the general scope of this paper. However, a more in depth treatment of this subject can be found in item 2 of the list of references.

6. CONCLUSION

Cost control to be effective must be instituted very early in the program. Once the size and weight. the vehicle configuration and equipments, and the major construction details have been established, it is very difficult to effect major cost reductions. DTC/LCC control procedures introduced in recent years can be very helpful in controlling costs throughout the development of the system.

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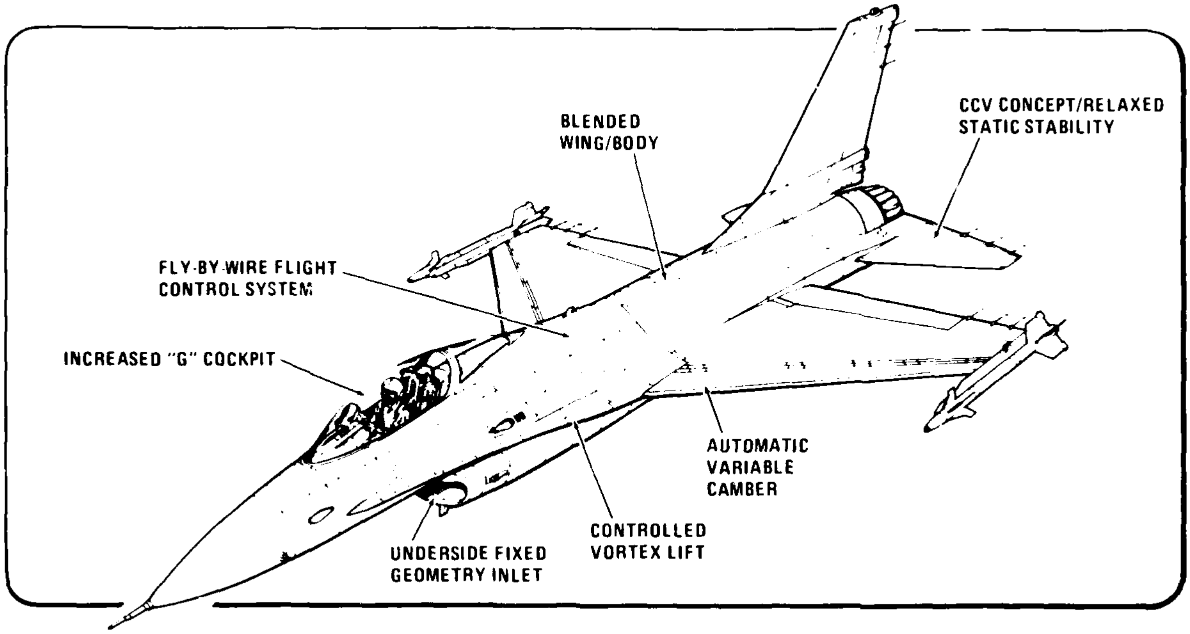
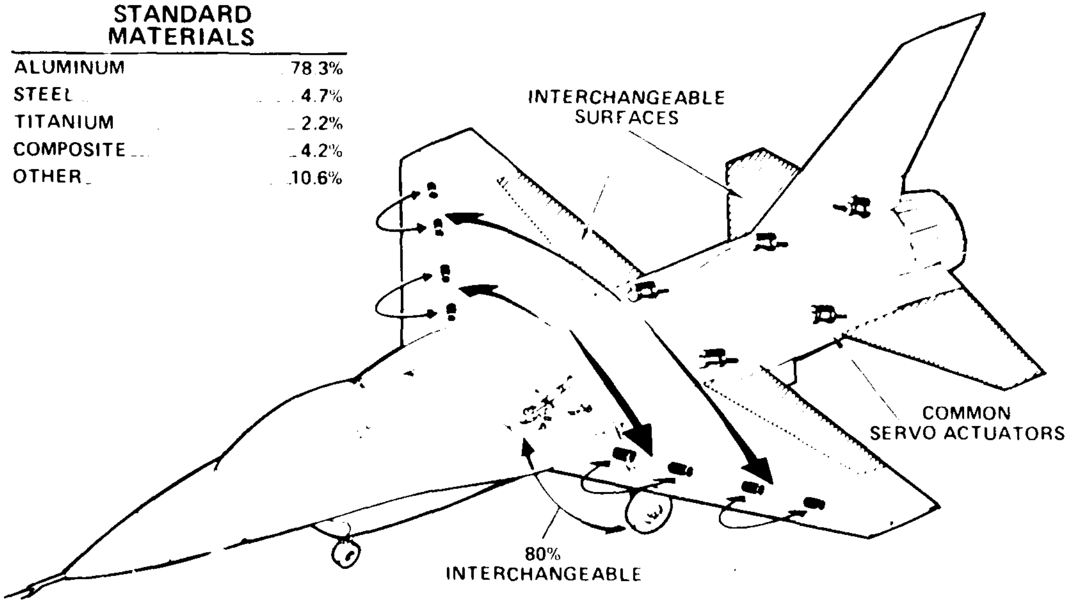


Figure 1 YF-16 Advanced Technologies and Design Features

STANDARD MATERIALS

ALUMINUM	78.3%
STEEL	4.7%
TITANIUM	2.2%
COMPOSITE	4.2%
OTHER	10.6%



USE OF EXISTING COMPONENTS	LIMITED FASTENERS	COMMON ENGINE
240 EXISTING & QUALIFIED 42 EXISTING BUT MODIFIED (329 Total)	50 STANDARD TYPES	P&WA F100 TURBOFAN

Figure 2 YF-16 Design to Cost Features

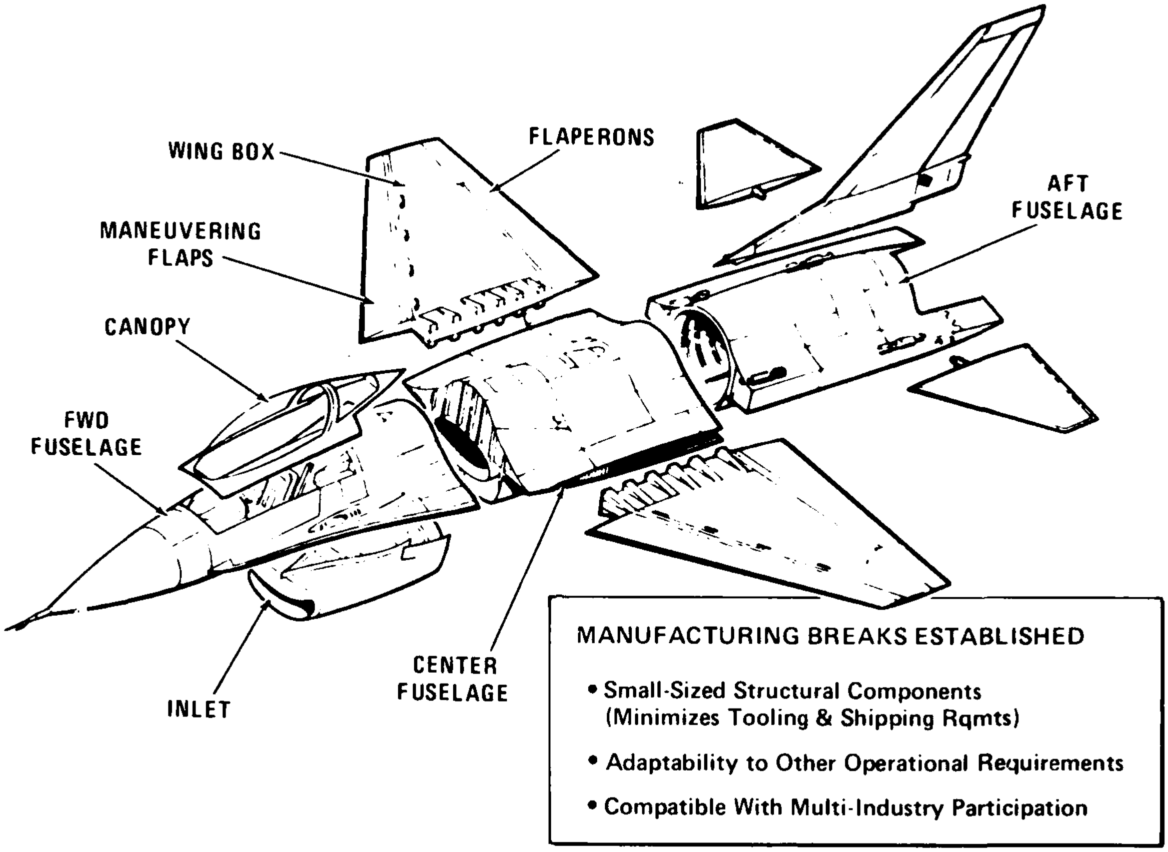


Figure 3 Producibility Enhanced By Modular Design

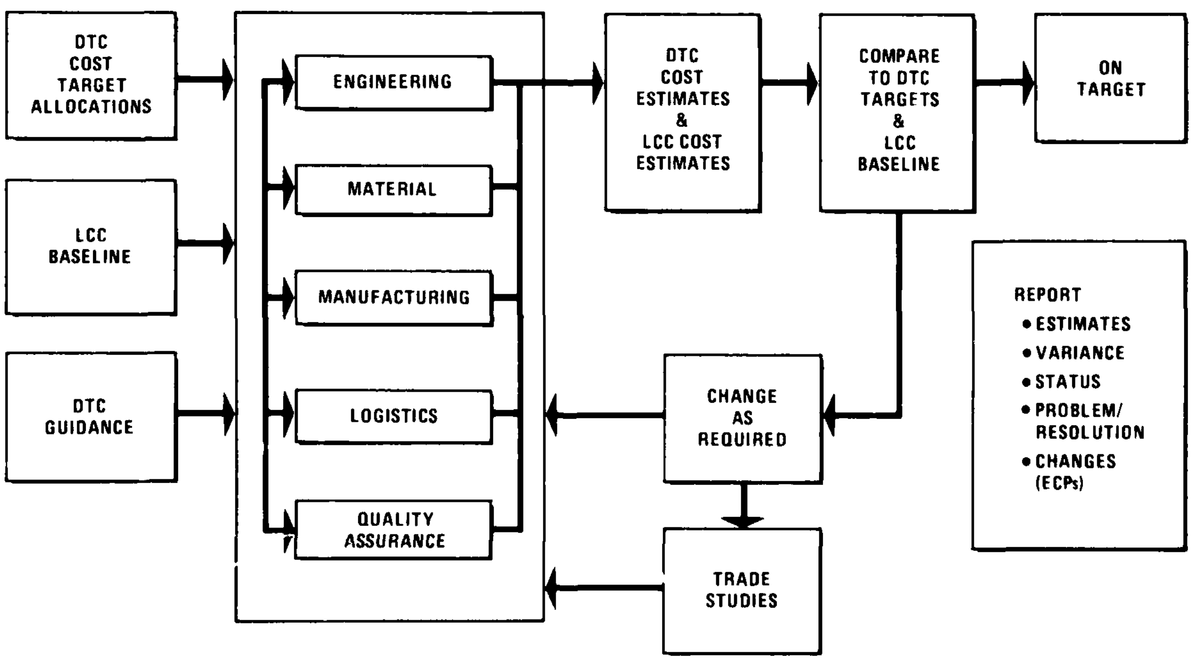


Figure 4 DTC/LCC Process

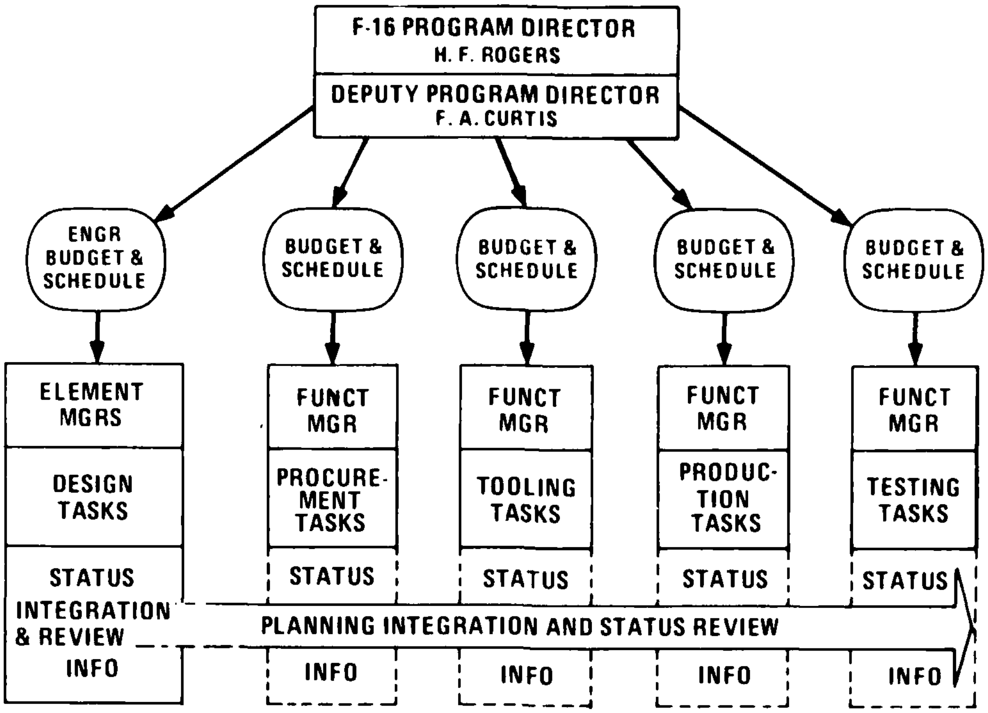


Figure 5 Element Manager Relationship to Top Management

- CUMULATIVE AVERAGE RECURRING FOR 1000 A/C
- CONSTANT FY 1975 DOLLARS
- NON-RECURRING , $38,474

WBS ELEMENTS			ENG'R		TOOLING		MFG		QA		PROCUREMENT			GD DTC TARGET
WBS	ELEMENT	LEVEL	HOURS	$	HOURS	$	HOURS	$	HOURS	$	RAW MAT'L	SUBSYSTEM	AVIONICS	
0000	Total Procurement	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	322,068	[illegible]
1000	Air Vehicle	2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	9,096	[illegible]	[illegible]	[illegible]	[illegible]
1100	Airframe	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	260,680	[illegible]		[illegible]
1110	AV Integr & Assy	4	[illegible]	[illegible]	[illegible]	18,388	[illegible]	[illegible]	[illegible]	[illegible]	19			[illegible]
1120	Fwd Fuse	4	63	1,336	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1,920	16,846		[illegible]
1130	Ctr Fuse	4	[illegible]	[illegible]	182	[illegible]	[illegible]	61,828	[illegible]	6,267	32,639			[illegible]
1140	Aft Fuse	4	38	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	258	[illegible]	24,206			[illegible]
1150	Inlet	4	[illegible]	[illegible]	[illegible]	983	[illegible]	7,063	98	[illegible]	[illegible]			[illegible]
1160	Wing	4	[illegible]	[illegible]	112	[illegible]	[illegible]	49,622	88	4,266	[illegible]			[illegible]
1170	Empennage	4	29	612	123	[illegible]	[illegible]	[illegible]	109	[illegible]	[illegible]			[illegible]
1180	Landing Gear	4	38	800	52	982	[illegible]	[illegible]	68	[illegible]	[illegible]	[illegible]		[illegible]
1190	Airframe [illegible]	4	167	[illegible]	288	[illegible]	[illegible]	[illegible]	383	[illegible]	[illegible]	208,071		[illegible]
[illegible]	Power Plant													
1300	Flight Control	3	28	[illegible]	[illegible]	[illegible]	2,082	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		271,562
1400	Avionics	3	382	[illegible]	[illegible]	[illegible]	[illegible]	16,601	[illegible]	[illegible]	[illegible]		322,068	366,386
1500	Armament	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8,176	[illegible]		79,655
1600	Weapon Delivery	3	25	560	[illegible]	[illegible]	1,660	[illegible]	[illegible]	1,706	[illegible]	110,978		150,257
1700	Other Avionic Equip	3	8	[illegible]	6	[illegible]	69	863		[illegible]	[illegible]			1,145
1800	Engr Analysis		649	[illegible]										15,412
5000	System/Project Mgt	2	2,019	63,287	20	390	103	1,330	1,230	11,669				76,676
5100	Engr Mgt/Sys Engr	3	1,230	28,209										28,209
5200	Support Project Mgt	3	789	15,078	20	390	103	1,330	1,230	11,669				48,467
5300	Cont Sys/Proj Mgt	3												
6000	Data	2	165	1,583										1,583
6100	TO's & Manuals	3												
6200	Engr Data	3	133	1,996										1,996
6300	Mgt Data	3	12	257										257
6400	Data Depository	3	-	1,330										1,330

Figure 6 DTC Target Allocations

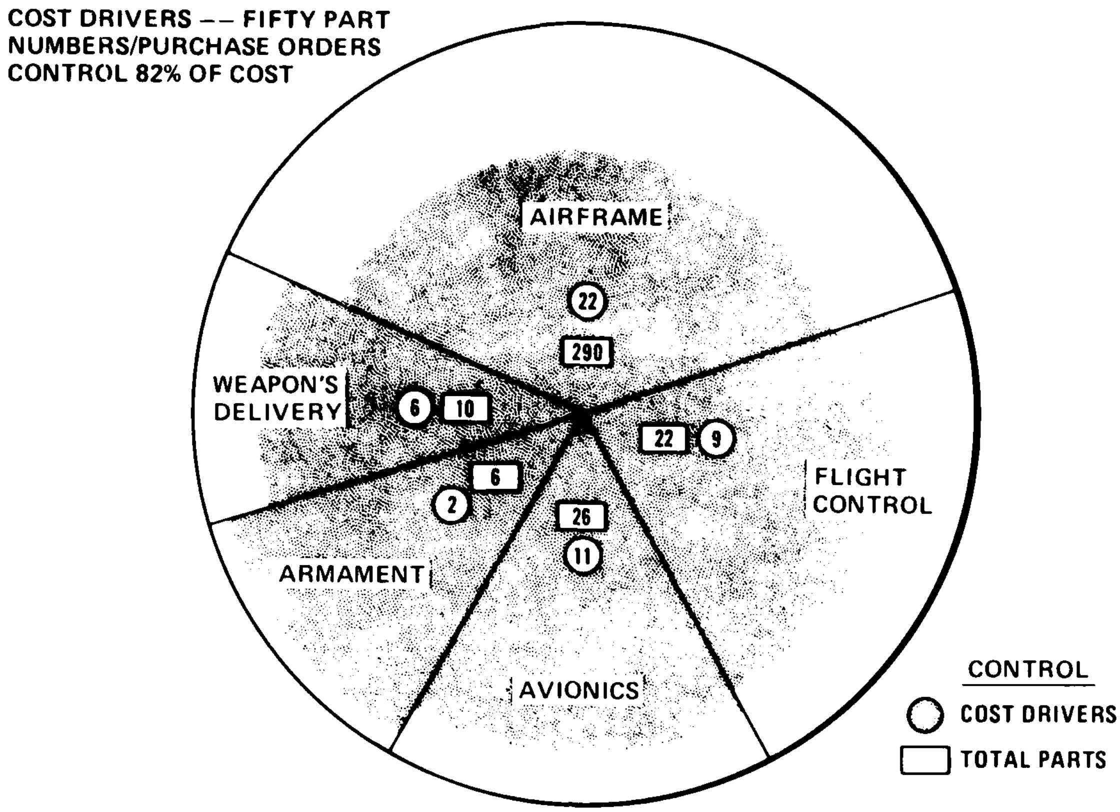
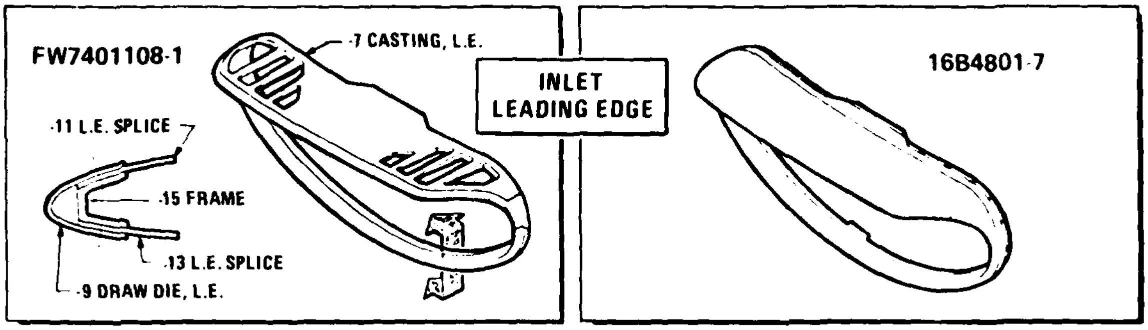


Figure 7 A Few Cost Drivers Comprise Most of The Cost

NUMBER OF TRADES	CATEGORY OF TRADE	TOTAL VALUE	IMPLEMENTED VALUE
	MANUFACTURING		
231	• PRODUCIBILITY	17,582,000	ALL
49	• STRUCTURAL	6,012,000	ALL
33	• EQUIPMENT	4,886,[illegible]00	ALL
14	• WEIGHT FOR COST	6,502,000	ALL
		$34,984,700	ALL
	PROCUREMENT		
35	• EQUIPMENT	19,127,200	ALL
14	• AVIONICS	6,391,000	ALL
15	• PROCUREMENT	16,777,000	ALL
6	• FORMAL	40,510,000	11,452,000
397		$82,805,200	$53,747,200
	TOTAL	$117,789,900	$88,731,900

Figure 8 Air Vehicle Trade Studies



CURRENT – CAST & BUILDUP

DETAIL PARTS	7
SUBASSEMBLY	1
FASTENERS	225
FAB TOOLS	9
NON-RECURRING TOOLING HOURS	536

EXAMPLE

FSD AIRPLANE	COST
MATERIAL DOLLARS	$ 122,054
FACTORY LABOR	8,132
TOOLING LABOR	16,654
Q.A. LABOR	1,995
TOTAL DOLLARS	148,835

650 AIRPLANE	COST
MATERIAL DOLLARS	$ 2,271,374
FACTORY LABOR	133,652
TOOLING LABOR	7,042
Q.A. LABOR	23,472
TOTAL DOLLARS	2,435,540

ALTERNATE-ONE-PIECE CAST

DETAIL PARTS	1
SUBASSEMBLY	0
FASTENERS	0
NON RECURRING TOOLING HOURS	259

FSD AIRPLANE	COST
MATERIAL DOLLARS	$ 80 904
FACTORY LABOR	1 429
TOOLING LABOR	8 542
Q A LABOR	450
TOTAL DOLLARS	91 329

SAVINGS $ 57,506

650 AIRPLANE	COST
MATERIAL DOLLARS	$ 1,387,918
FACTORY LABOR	23,586
TOOLING LABOR	3,598
Q A LABOR	4,153
TOTAL DOLLARS	1,419,225

SAVINGS $1,016,315

Figure 9 Typical Structural Trade

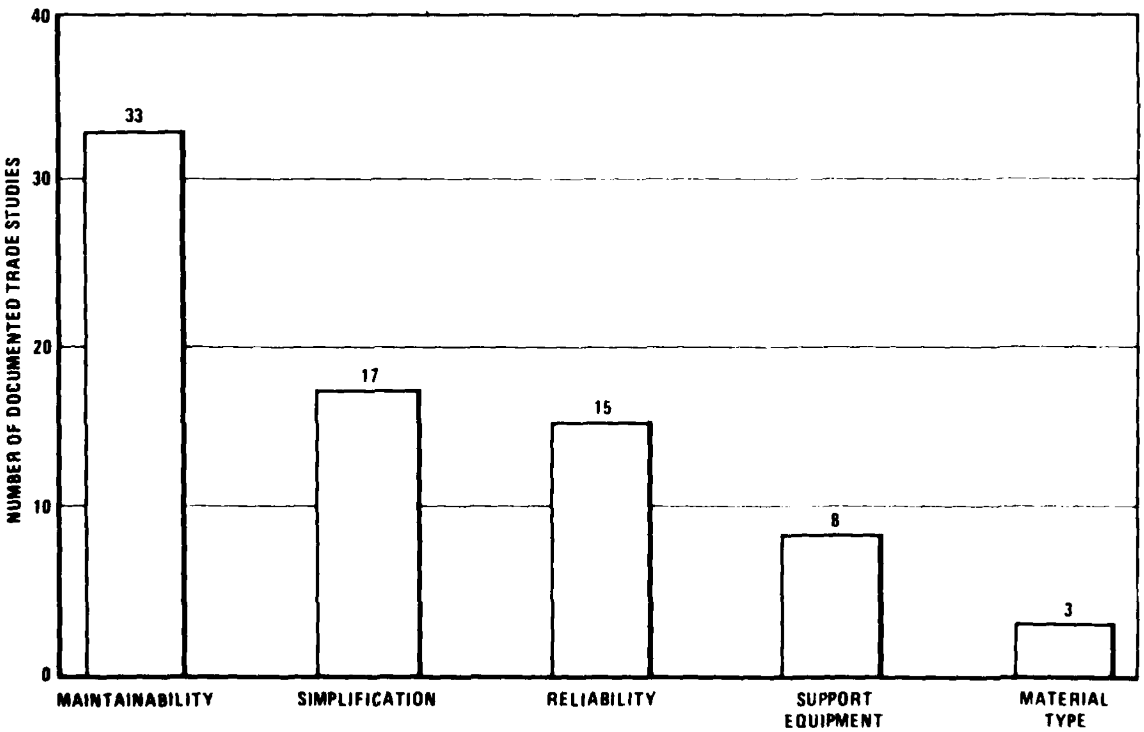


Figure 10 Distribution of Supportability Trade Studies

STRUCTURAL INTEGRATION AS A MEANS OF COST REDUCTION

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ABSTRACT

The cost of the structure became as important as weight. By the means of some components of the Tornado fighter aircraft it is demonstrated how the costs can be reduced by structural integration. The components are two flat panels, the wing carry through box and the Taileron. Cost savings could be achieved from 15% to a maximum of 68%.

1. INTRODUCTION

The ever increasing requirements of the overall performance of modern fighter under the consideration of minimum weight leads to very sophisticated structure. This could lead to a dramatic cost increase, which would cause a reduction of the effectivity of the system.
Therefore, it is a basic task that the designer is controlling the cost of the product from the beginning as diligently as he has done for weight in the last 50 years.
One very efficient method amongst others to keep the cost down is to minimize the number of parts by means of structural integration. In this paper the effectivity of that method will be demonstrated on some structural components of the Tornado fighter aircraft. (Fig.1)
The Tornado is a multi role combat aircraft in the Mach 2+ category.

2.METHODS FOR COST REDUCTION

A method for reduction of the cost per unit is to increase the number of the aircraft and production rate. This is absurd for one country only, because it leads to reduction of the unit cost by increasing the overall cost of the fleet. The way to overcome this absurdity is a bi- or multi-national co-operation.This is the case of the Tornado which was developed by FRG, Italy and the UK and is now in production in those countries. This is only effective if worksharing is practised; that is, one country manufactures the components of the whole fleet as a single source. In the case of Tornado the tri-national co-operation caused an increase in the number of aircraft from 320 units for German requirements to more than 800 units with a delivery rate of 8 to 10 units per month.

In FRG the centre fuselage and the wing carry through box is being manufactured, in Italy the wings and in the United Kingdom the cockpit, the aft fuselage (engine section), the vertical stabilizer and the differential movable horizontal stabilizer, the so called Taileron.

For 800 unites it is worth investing in production equipment and tooling to rationalize the manufacturing process. By NC machining, automatic cutter change and so on, cost savings can be achieved, but this automation can be performed for part manufacturing only.

In addition the usage of the die-forged parts cuts the cost down and it is evident that the forging is not very efficient for a set of only 100 aircraft, which is the requirement of Italy.
Die-forging and the optimisation of the cut of raw material reduced the worked up raw material for the centre fuselage about 38%.

But even with optimised tooling the assembly remains a manpower consuming task.Therefore it is obvious that a further cost reduction can be achieved only by reduction of the amount of parts which have to be assembled. This must be done by structural integration.

This is the last link in a chain where the cost of an aircraft unit can be influenced. On a political level the decision must be taken about co-operation and the number of aircraft, which are linked together. The management must decide which investment is to be made. The men at the drawing board influence the number of parts and have a good deal of the responsibility for the cost.

3. DEMONSTRATION OF COST SAVINGS ON SOME COMPONENTS

On some components of the primary structure of the Tornado that achieved cost savings, due to the reduction of the number of parts by means of structural integration, will be demonstrated. These are two flat panels, both carrying bending and shear forces, the central wing carry through box and the Taileron. The improvements of the panels and the wing carry through box were performed in the productionizing phase whilst the work on the Taileron is a joint task of BAe and MBB for product improvement by application of advanced technologies on that component.
These components have been chosen because the cost saving has been achieved by different engineering approaches.

a) change of design principles

In the case of the panels, the design principle has been changed. The prototype structure is a built up structure whilst the production one is a sandwich construction.

b) improved engineering

The improvements for the wing carry through box were obtained by excellent engineering. This is a good example for the importance of a productionizing phase, because the conditions during the prototype phase are not given, i.e. high investments, LLI (long leed items), expensive dies, tools, etc.

c) advanced technology

The Taileron demonstrates that by the change of technology from a metal design to a Carbon Fibre Reinforced Plastic (CRP)design, cost and weight reduction can be obtained. In Fig. 2 the structure of the centre fuselage of the Tornado is shown and the components to be discussed are identified.

3.1 Sandwichpanel (change of design principle)

The first example to be discussed is a panel of the upper surface of the centre fuselage. It is a primary structure and has to carry forces caused by bending and shear. The prototypes have a sheet metal assembly that is a box type structure with an upper and lower skin stiffened by extensions or arms of the frames and bulkheads. The lower skin is the upper surface of the wing pocket, which carries part of the wing slot seal.

When the wing is in the forward swept position, it must not be a gap between the wing root and the fuselage. Therefore the root of the wing aft of the pivot point interferes with the fuselage if the wing is being swept back and a pocket in the fuselage is therefore necessary. The panel does not buckle at limit design load.

For the series aircraft the design principle was changed. (Fig. 3) Instead of a sheet metal assembly, a sandwich construction was chosen. This caused a 47% reduction of parts to be assembled, a 71% reduction in fasteners, a cost saving of 24% and a weight saving of 4,0%. The number of fasteners per kg, which is a cost driver, dropped from 36,7 to 11. Most of the decrease in the number of parts were obtained by elimination of most of the frame arms.

As a second example for that approach, the lower panel of the main undercarriage bay will be considered. (Fig. 4) That panel is also primary structure. The panel of the prototype is a skin-stringer construction stiffened by arms of frames and bulkheads. The skin is part of the lower surface of the fuselage and does not buckle up to limit design load. For the series aircraft, again a sandwich construction was chosen, which gave a 22 % reduction of the quantity of parts, a 80 % reduction of fasteners and a cost saving of 30 %. The number of fasteners per kilogramme dropped from 116 to 10. The weight of that part increased by 10 %. This weight increase is to be seen in relation to the overall mass of the structure, because the stiffer sandwichpanel caused a redistribution of the internal loads and took more load than the weaker prototype panel. Therefore, other components of the lower structure of the fuselage became lighter and results in a small overall weight saving.

In that particular case the sandwich construction has an additional advantage. The bottom of the undercarriage bay has a smooth surface and is therefore easier to clean. The cost reduction was achieved although bonding jigs are expensive, but a lot of other tools and jigs could be eliminated. In these two cases preassembling of the panels was not possible because of the frame arms were one piece with the frame.So the assembly has to be performed in the main assembly jig which increases the holding time. In general the work load in a main assembly jig is very high and one should always try to do as much work as possible in subassemblies.
These two examples obviously showed that a sandwich construction can lead to a significant cost reduction. In a sandwich structure the functions of stringers and ribs are structurally integrated in the honeycomb assembly.

3.2 N/C machined and E/B welded wing carry through box

The wing carry through box is structurally not integrated in the overall fuselage structure. (Fig. 5) It is a seperate component sustained by 6 links or posts at its lower surface and fitted to 6 longerons at its upper surface. The parts are N/C machined and E/B welded except the upper plate which is bolted to the welded "bath-tub". Mounted to the wingbox is the wing sweep actuator fitting.
Although in general the design principles were not changed from prototype to series structure a significant cost and weight reduction could be realized by thorough enginee-ring.
The use of some components of the wingbox, the actuator fitting and finally the wing box itself will demonstrate how structural integration influence the cost and the weight.

The rear sidewall (Fig.6) of the prototypes which is the shear web of the box in the y-z plane, was built by 6 parts welded together and 6 parts bolted on.The angles are bolted on the sidewall joining the ribs with the sidewall.
In the series design the 6 angles and the upper flanges,which were E/B welded to the shear web in the prototype design, were structurally integrated and the parts of the web to be welded together reduced from 6 to 2.The number of parts were reduced from 12 to 2, the number of weld seems from 5 to 1 and fasteners were eliminated completely. A weight saving of 37% could be achieved partly by this structural integration and partly by better engineering. The cost dropped to 44% of the prototype design.

A further example which will be presented is the wing sweep actuator fitting. (Fig. 7) This fitting is mounted to the wingbox and is stressed by symmetrical and asymmetrical loads of the wing sweep actuator.
It is a class I part, that means a failure of the fitting causes a loss of aircraft. It is a highly loaded fatigue critical item.
The actuator fitting of the prototypes is a hybrid framerod design whereas the series fitting is a classical strut design. This is the only component of the wing carry through box for which the design principles were changed from prototype to series.

Before we will discuss the cost saving parameters we should say a few words about the different designs. The series fitting has a very clear load path although it is a statically indeterminate structure.There are only a few notches, but these are well known engineering elements i.e. lugs. By the reason of the static redundancy the fitting is fail safe with regard to a failure of strut, which is very desirable for such a vital component. The fail safe capability was proven by test.
The prototype fitting is a complex structure where the load paths are difficult to comprehend.
There are a lot of notches and in the event of an existing crack you have to rely on a small crack growth.
The reduction of the number of parts is high and the reduction of fasteners extremly high, this is not clearly seen in the figure. The series design has only 41% of the number of parts of the prototype design and only 14% of the amount of fasteners. In addition some of the parts of the series design are identical thus the number of different parts drop from 9 to 4.
This all results in a cost saving of 68% and a weight saving of 15%.
The example clearly shows that a cost reduction and weight saving can be achieved together with an improvement of performance of the component with a thorough design.

Two components of the wing carry through box are shown in detail and will be representative for the whole box. The wing carry through box is a highly loaded structure.(Fig8) The loads in the pivot lugs are up to 4500 KN (UDL) and the loads in the links by which the box is attached to the fuselage are up to 1600 KN. The box, as previously defined, is a class I structure.
The material of the welded components and the webs is Ti 6AL 4V, whereas the material of the upper panel is Ti 6AL 6V 2Sn. The latter material has an advantage in the range of elastic plastic compression stresses. The reason is the requirement to inspect and machine all weld seems. All fittings and lugs (except the wing sweep actuator fitting), where titanium was the lightest choise of material are structurally integrated in the wing box. The upper and lower plates are integral machined plates. All components are machined from plates or forgings except the internal ribs which are made from sheet metal. It should also be mentioned that the wing box is used as an integral fuel cell.

The re-design of the wing box gave a weight saving of 16% and 20% less parts. The amount of fasteners dropped by 29%. This results in a cost saving of 33% for the series wing carry through box.
It is interesting to note that the number of parts per kg remains almost unchanged, because the weight reduction and number of part reduction is nearly the same. The number of fastener per kg was diminished from 1.67 to 1.42.
These examples obviously demonstrate again how sensitive the costs are with regard to the number of parts and how the cost can be reduced by structural integration.

3.3 Composite structure

Advanced technologies which give significant weight reduction should not cause an increase in cost . BAe and MBB developed a CRP Taileron which will be compared with the existing metal Taileron. The design goal was to demonstrate weight reduction but the manufacturing cost had to be at least equal to or less than that for the metal Taileron.
The metal Taileron consists of an inner ,highly loaded, box type structure with ribs and integral machined stiffened skins.(Fig.9) The less loaded rear and outboard parts are a full depth honeycomb construction. The leading and trailing edges are seperate parts. All these components are bolted together. The Taileron is mounted on a spigot, which is attached to the fuselage structure.
The CRP-Taileron is a full depth honeycomb, except in the spigot area.(Fig.10) There also exists a CRP substructure. Part of the root rib with the bearing housing and the integrated actuator lever as well as the outboard bearing housing, is made out of aluminium. Possibly this is not the lightest structure but with regards to the cost it is an engineering optimum.

The honeycomb is of course a bonded structure whereas the substructure is preassembled and bolted in. The carbon skins are built up from 6 to 64 plies. The material used is the Ciba prepregsystem 914C with the XAS fibre by Courtaulds. The lower skin has an access hole which is required to secure the outboard bearing where the y-loads are carried. The leading and trailing edges are seperate parts. The material of the leading edge is Glass Fibre Reinforced Plastic (GRP), and that of the trailing edge CRP.

A comparison of both designs shows that the CRP-Taileron has only 25% of the number of parts of the metal Taileron and 42% of the fasteners. A weight reduction of 18% together with a 15% cost reduction could be achieved . At first this result is surprising due to the fact that the material cost for CRP are much higher than that for metal, but keeping in mind that the waste material for a machined metal component is 75% to 90% whereas the waste cut off for the Carbon prepreg ist 15% to 25%. Therefore the influence of the higher price for the material loses its importance on the cost of the CRP component. It should be stated that the estimate of cost for CRP-Taileron is based on engineering drawings and on manufacture expertise of prototype but not yet on an actual series production component. Compared with the previous results the cost saving for the CRP-Taileron must be conservative.

4.SUMMARY

By the means of some primary structural components of the Tornado fighter aircraft it demonstrates how cost can be reduced by structural integration. With the exeption of the CRP Taileron the data were not calculated but experienced in the shops and compared with cost of fully assembled component of a prototype aircraft with one of the first series units. Cost reductions, due to improved tooling, batch manufacturing, in general by optimisation of the whole manufacturing processes are not included.
The presented cost reductions are due to a re-design only. Naturally the designer must have communication with the man in the shops to achieve an optimum of design to cost. The described components were chosen as examples for different approaches, which led to the cost reductions:

a) change of design principles, in specific cases change from sheet metal design to a sandwich component (upper and lower panel)

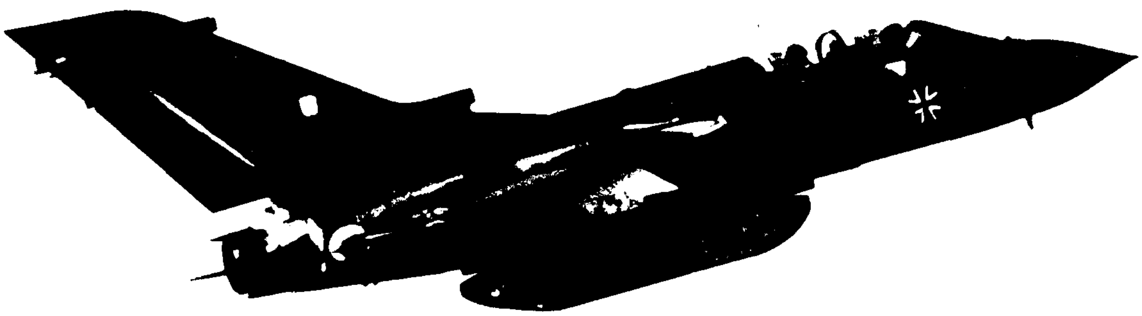
b) improved engineering and optimisation of an existing design without a change of the design principles (N/C machined and E/B welded wing box)

c) change of technology (CRP-Taileron)

A summary of the presented data is given in Fig 11,12 and 13. The figures show the amount of reductions in relation to previous design. An analysis of the data leads to a very simple and therefore often forgotten ground rule for design:

Keep the number of parts and fasteners
at a minimum.

This ground rule, as well as every other rule, must be applied "cum grano salis". If the structural integration leads to a non standard raw material size it might be that two parts are cheaper than one.



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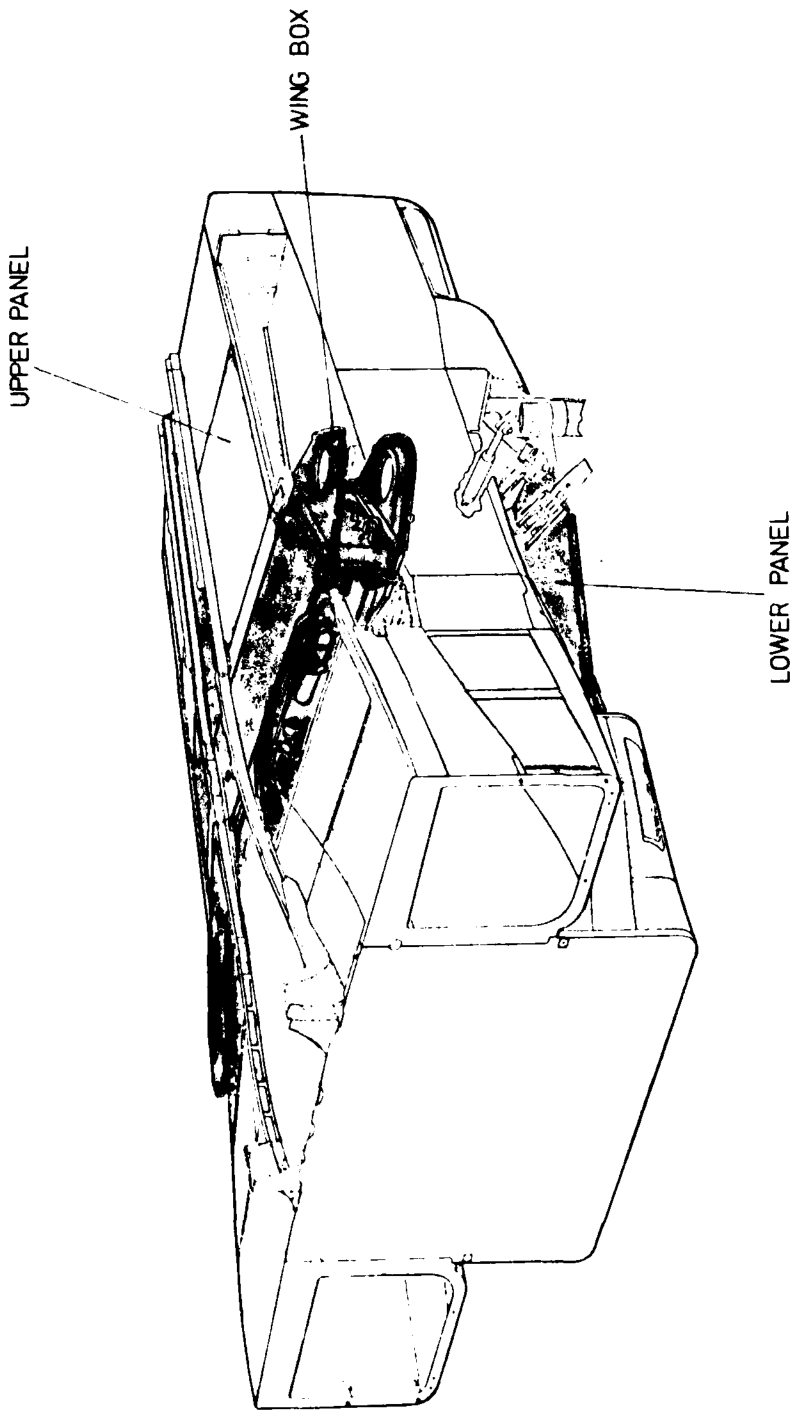
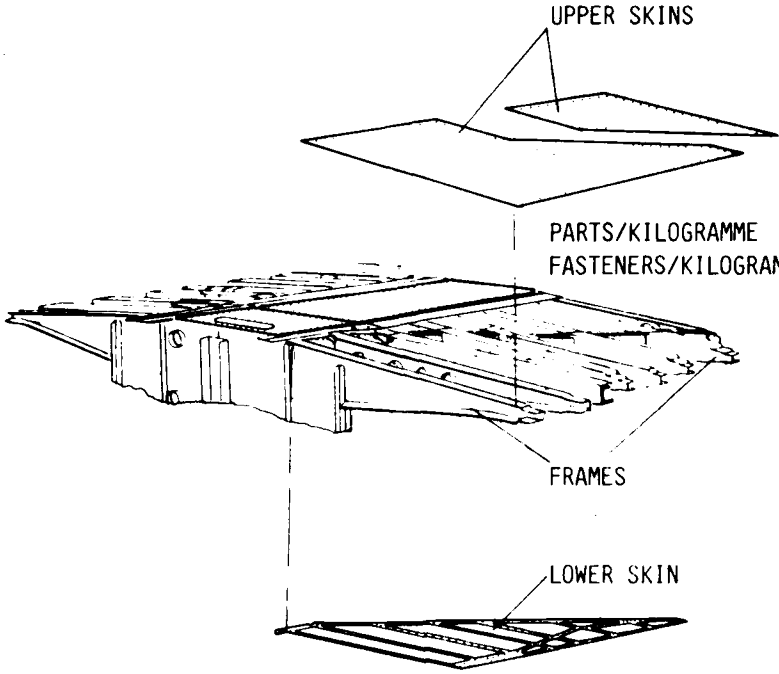


FIG. 2 CENTRE FUSELAGE STRUCTURE

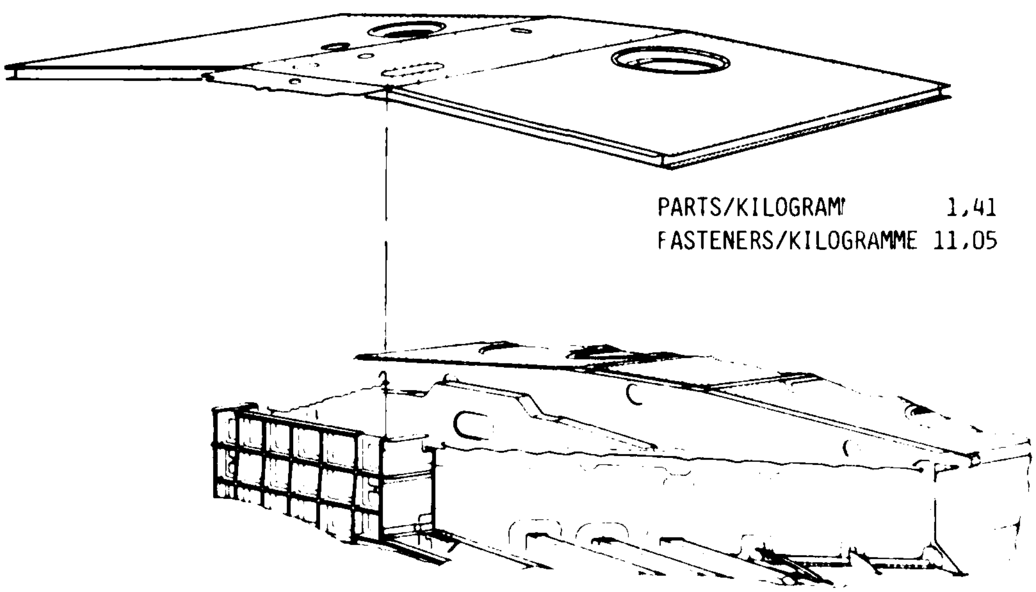
SHEET METAL ASSEMBLY



PARTS/KILOGRAMME 2,55
FASTENERS/KILOGRAMME 36,70

METAL SANDWICH ASSEMBLY

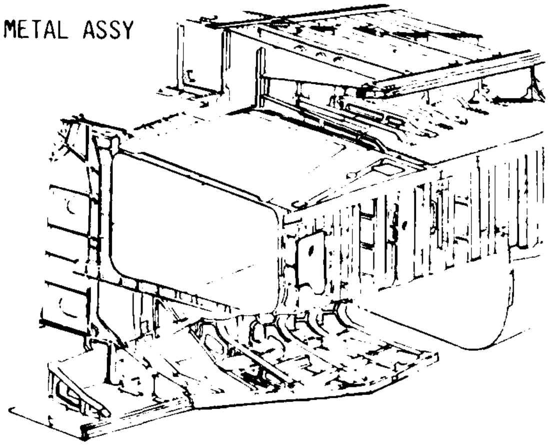
SHEET METAL ASSEMBLY	100%
REDUCTION OF PARTS	47%
REDUCTION OF FASTENERS	71%
MASS REDUCTION	4%
COST REDUCTION	24%



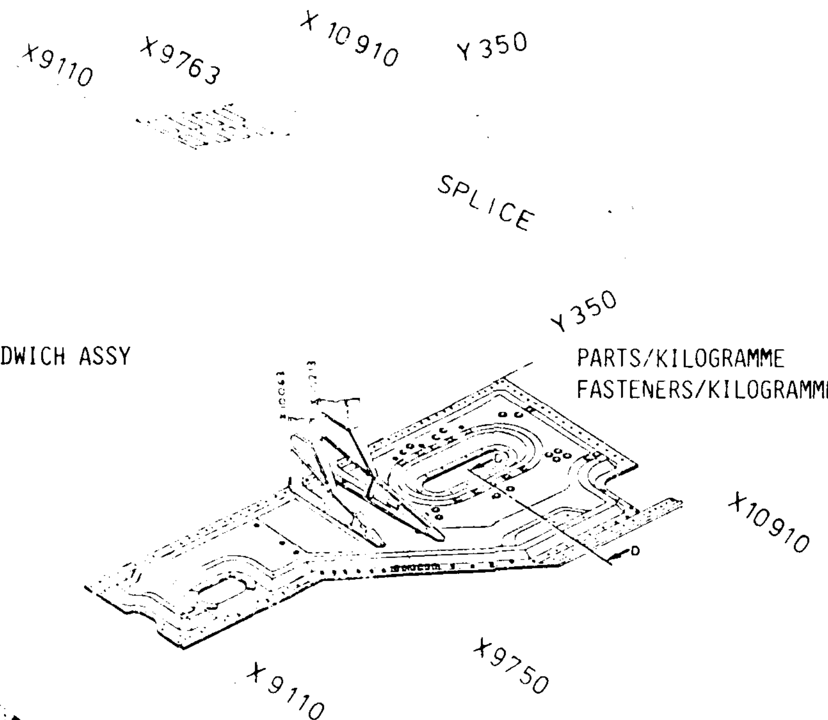
PARTS/KILOGRAMME 1,41
FASTENERS/KILOGRAMME 11,05

FIG. 3 UPPER PANEL

SHEET METAL ASSY

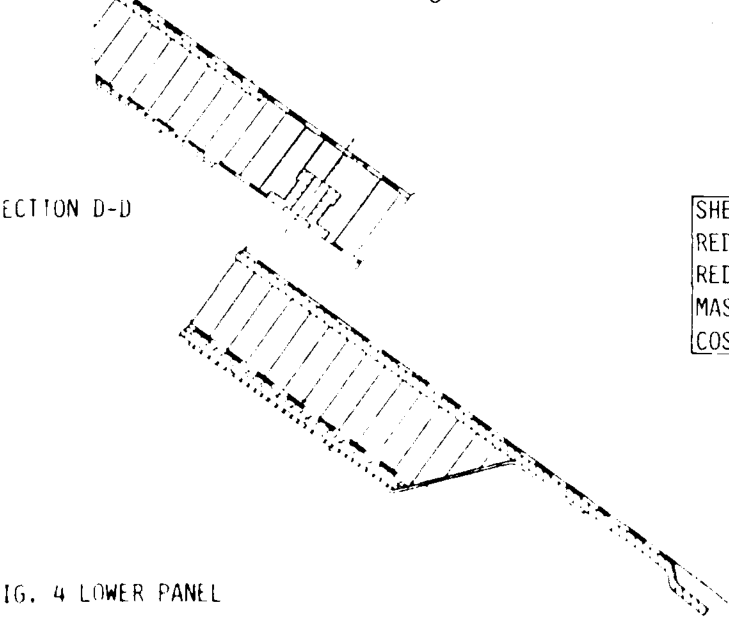


PARTS/KILOGRAMME 8,7
FASTENERS/KILOGRAMME 154,0



METAL -SANDWICH ASSY

PARTS/KILOGRAMME 5,9
FASTENERS/KILOGRAMME 22,5

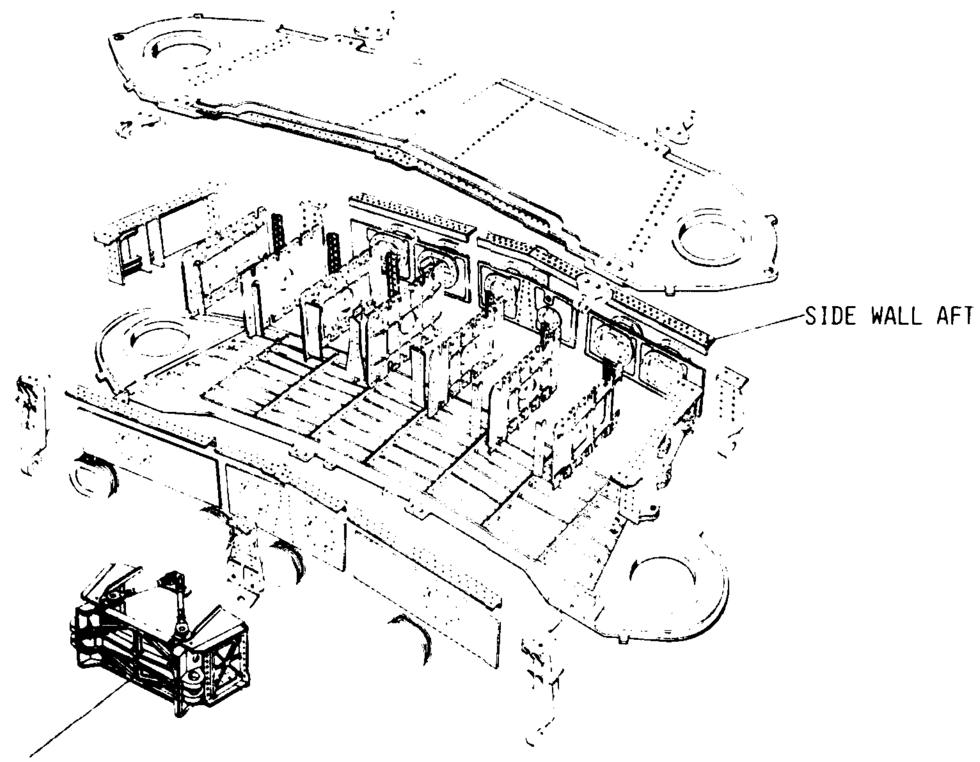


SECTION D-D

SHEET METAL ASSY	100%
REDUCTION OF PARTS	22%
REDUCTION OF FASTENERS	80%
MASS INCREASE	10%
COST REDUCTION	30%

FIG. 4 LOWER PANEL

PROTOTYPE WING BOX



PRODUCTION
WING BOX

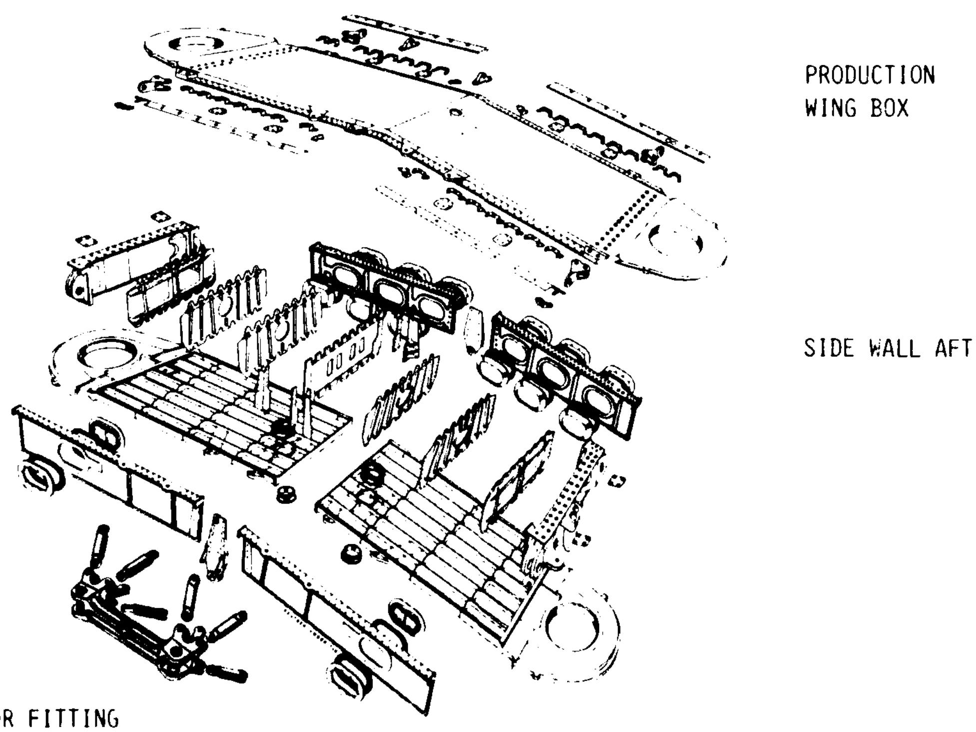
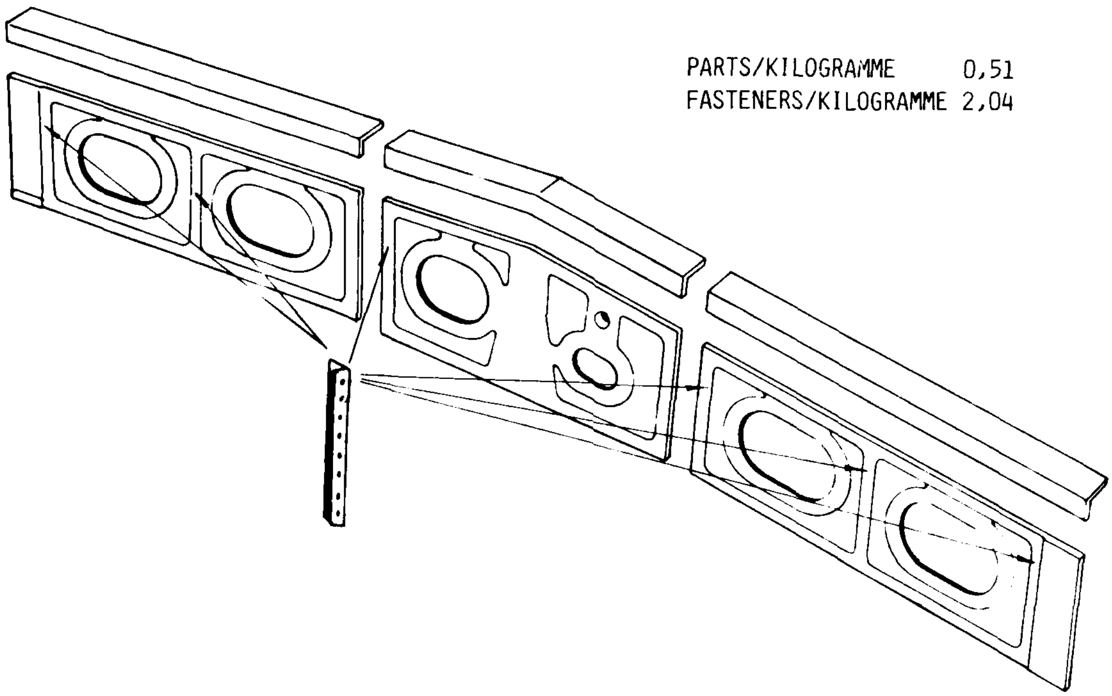


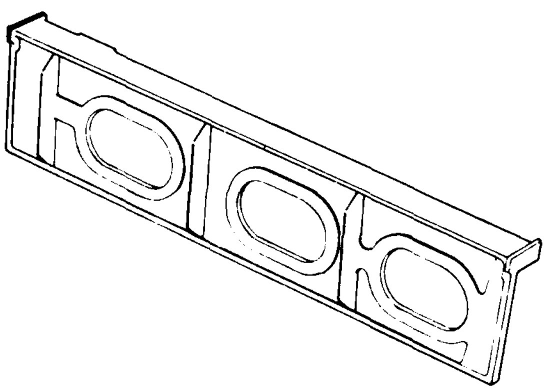
FIG. 5 WING BOX: EXPLODED VIEW

BOLTED AND WELDED ASSY

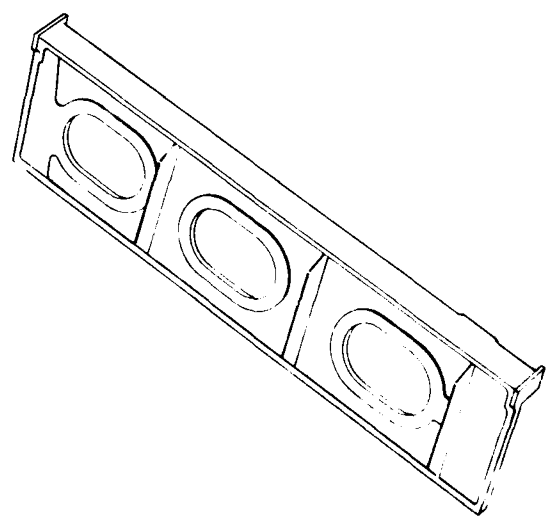


PARTS/KILOGRAMME 0,51
FASTENERS/KILOGRAMME 2,04

INTEGRATED FLANGE DESIGN



PARTS/KILOGRAMME 0,13
FASTENERS/KILOGRAMME --

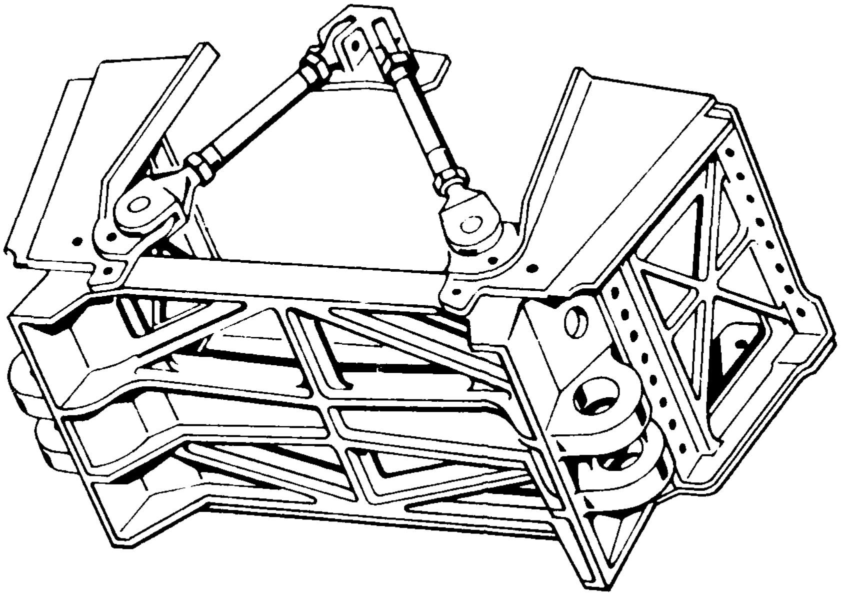


BOLDED AND WELDED ASSY	100%
REDUCTION OF PARTS	83%
REDUCTION OF FASTENERS	100%
MASS REDUCTION	37%
COSTS REDUCTION	56%

FIG.6 WING BOX SIDE WALL AFT.

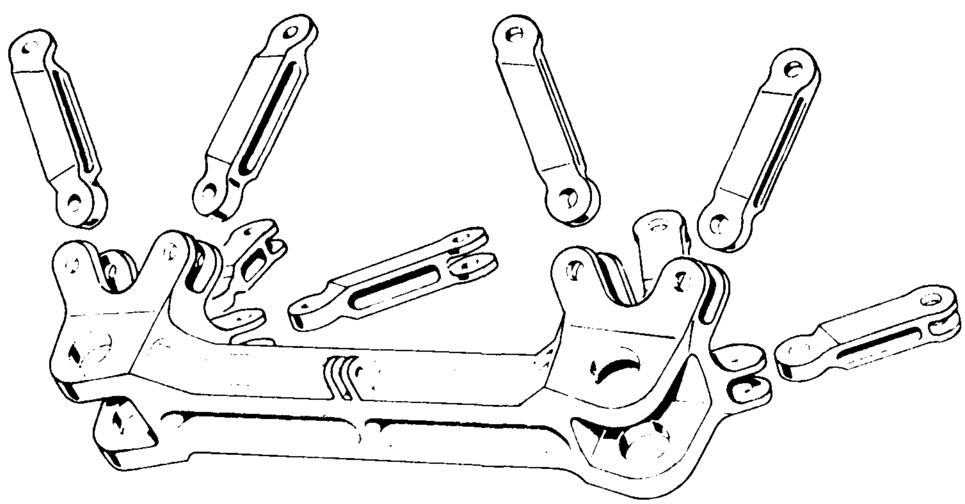
ACTUATOR SUPPORT (BOX DESIGN)

PARTS/KILOGRAMME 0,82
FASTENERS/KILOGRAMME 4,33



BOX (DESIGN)	100%
REDUCTION OF PARTS	59%
REDUCTION OF FASTENERS	86%
MASS REDUCTION	15%
COSTS REDUCTION	68%

ACTUATOR SUPPORT (STRUT DESIGN)

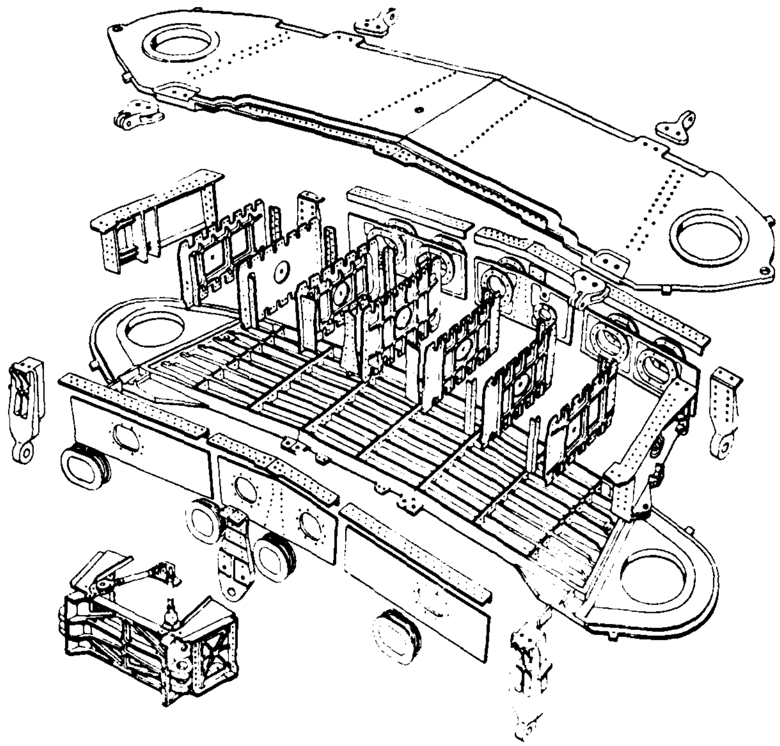


PARTS/KILOGRAMME 0,39
FASTENERS/KILOGRAMME 0,7

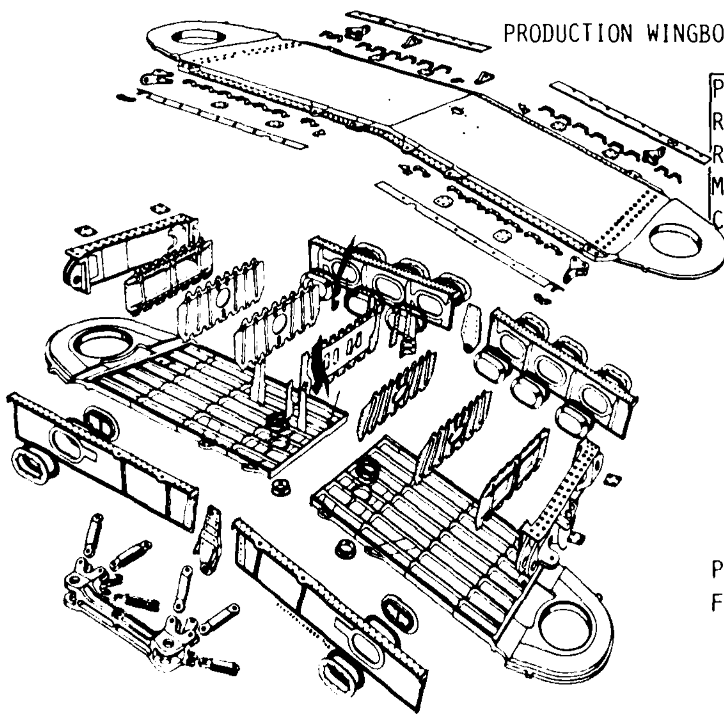
FIG.7 ACTUATOR FITTING

PROTOTYPE WINGBOX

PARTS/KILOGRAMME 0,28
FASTENERS/KILOGRAMME 1,67



PRODUCTION WINGBOX



PROTOTYPE WINGBOX	100%
REDUCTION OF PARTS	20%
REDUCTION OF FASTENERS	29%
MASS REDUCTION	16%
COST REDUCTION	33%

PARTS/KILOGRAMME 0,27
FASTENERS/KILOGRAMME 1,42

FIG. 8 WING BOX ASSEMBLY

PARTS/KILOGRAMME 1,46
FASTENERS/KILOGRAMME 17,33

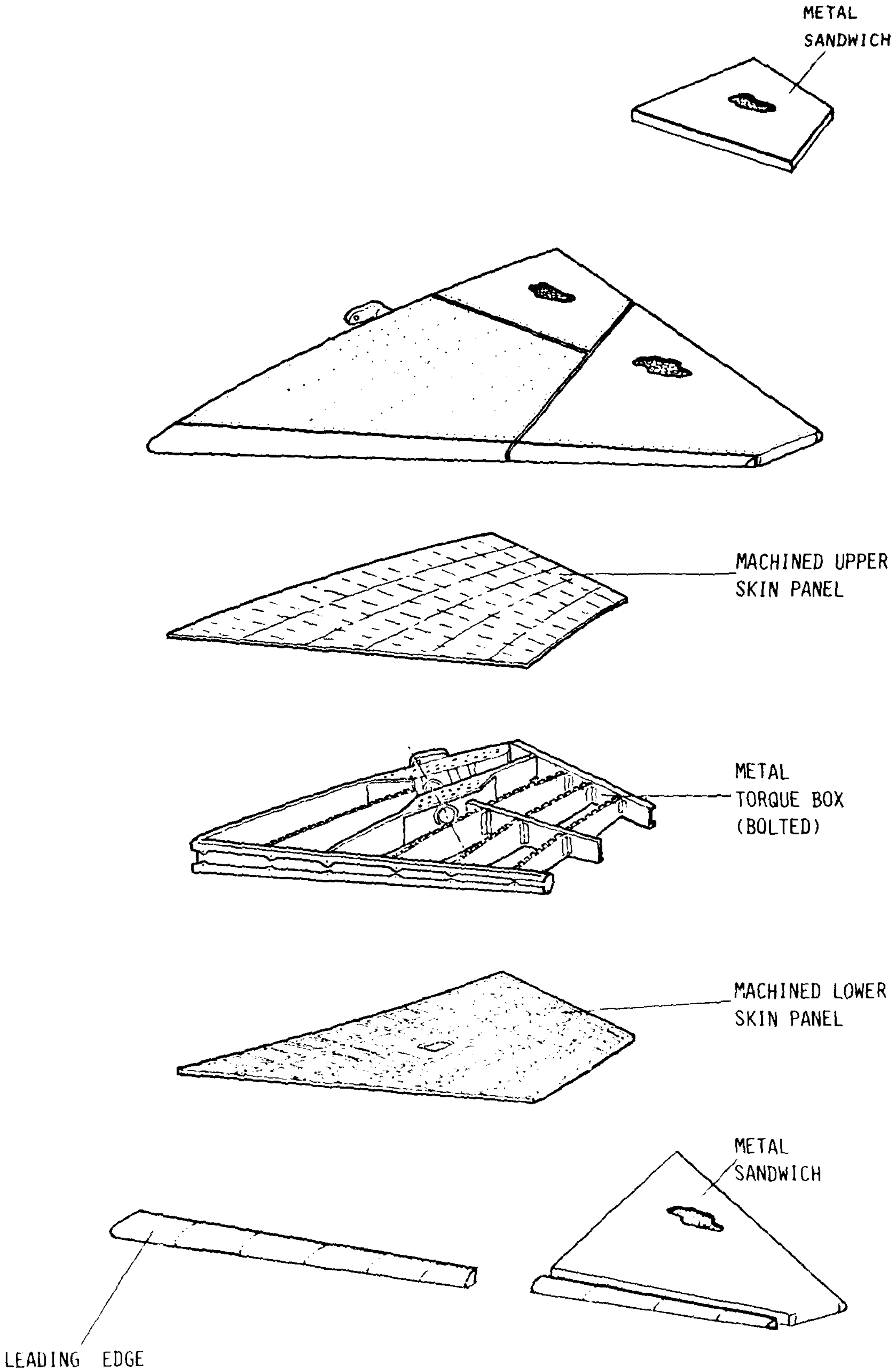


FIG.9 METAL TAILERON

METAL TAILERON 100%
REDUCTION OF PARTS 75%
REDUCTION OF FASTENERS 58%
MASS REDUCTION 18%
COST REDUCTION 15%

PARTS/KILOGRAMME	0,44
FASTENERS/KILOGRAMME	9,12

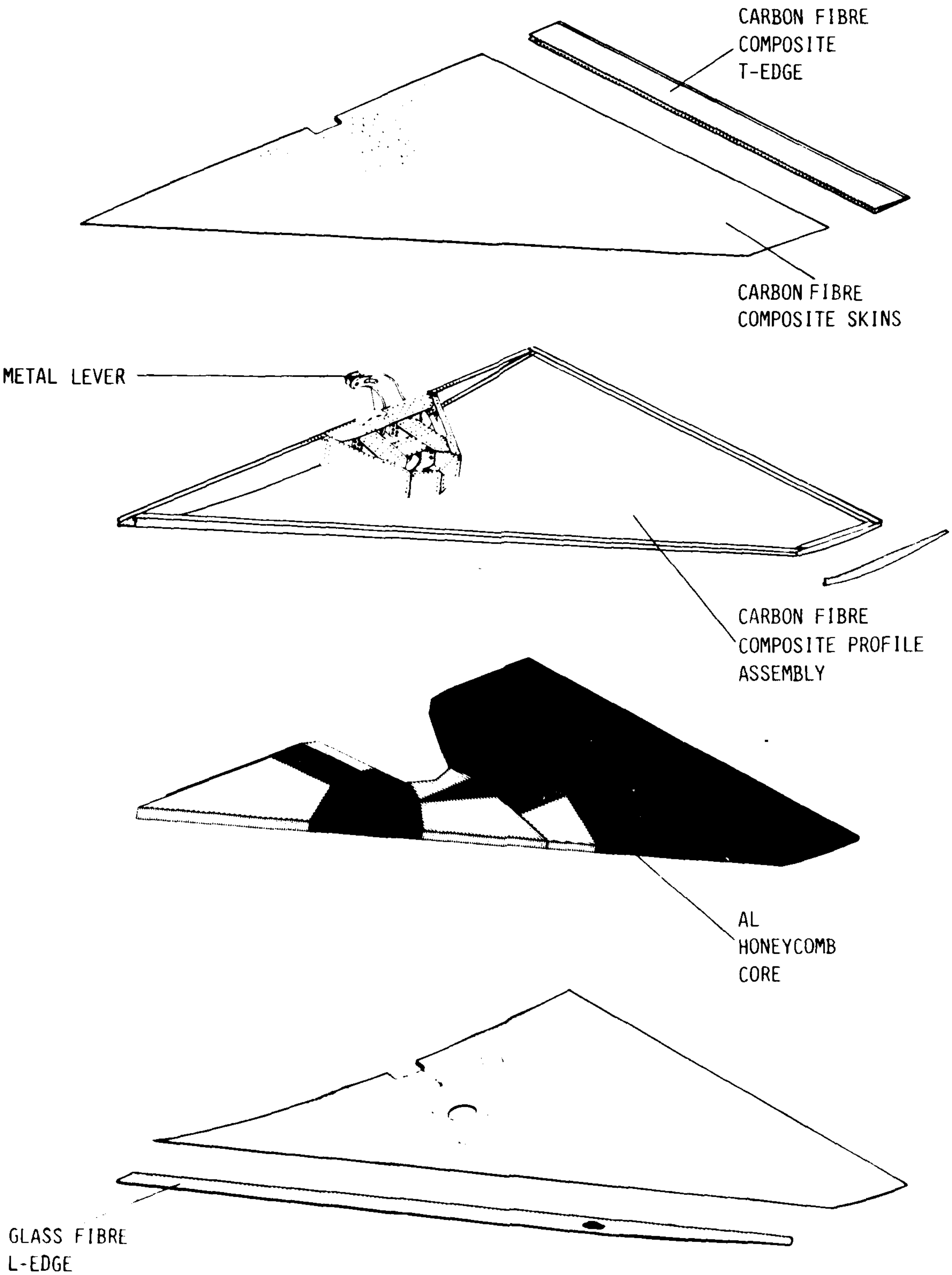


FIG. 10 CARBON FIBRE COMPOSITE TAILERON

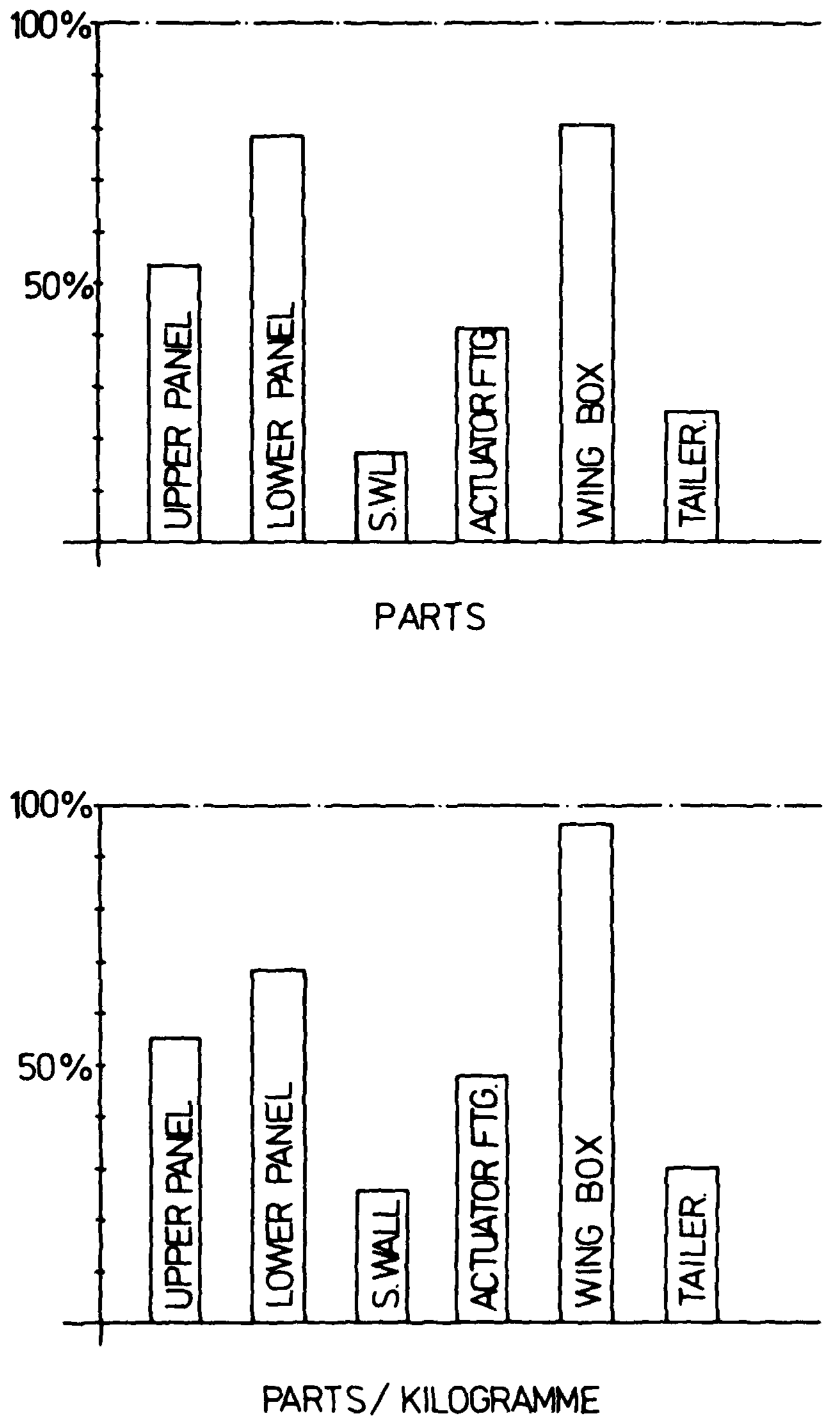


FIG. 11 PART REDUCTION

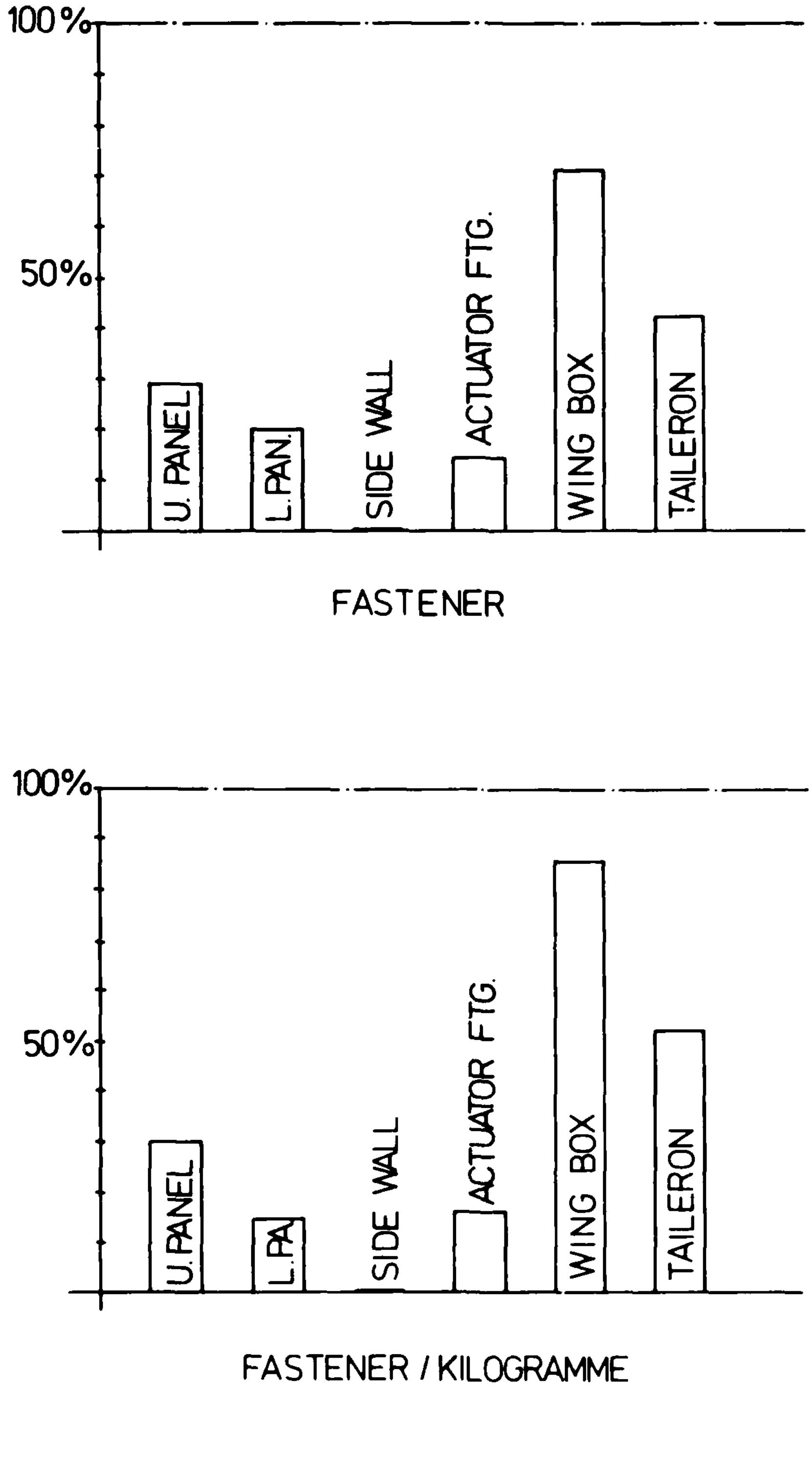


FIG. 12 FASTENER REDUCTION

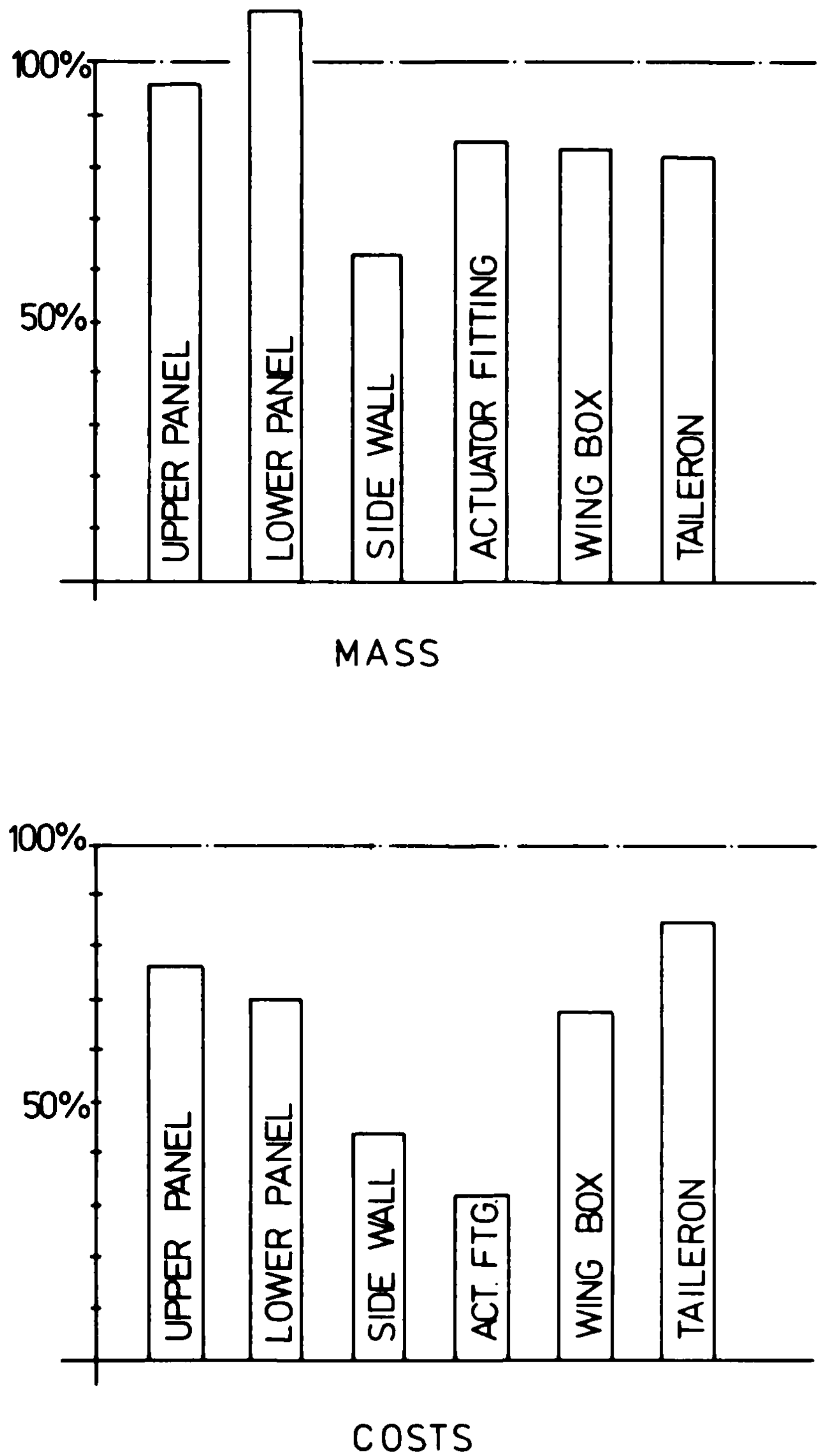


FIG. 13 MASS AND COSTS SAVING

DESIGN-TO-COST ET TECHNOLOGIES NOUVELLES

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AVIONS MARCEL DASSAULT BREGUET AVIATION
78, quai Carnot 92214 - Saint-Cloud -

RESUME

Le projet d'un avion de combat moderne ne peut plus être entrepris sans faire intervenir le coût à l'égal de la mission ou des performances dans les compromis qui conduisent au choix d'une formule d'avion. Ces compromis sont fondés sur les technologies dont on pourra disposer au moment du démarrage de la production. Il s'agit en particulier de technologies nouvelles qui ont quitté le stade du laboratoire et sont entrées en application sur des avions existants avant d'être intégrés à plus grande échelle dans le projet. La technologie des composites Carbone-Epoxy est en matière de structure une des plus remarquables. Son introduction au stade projet se traduit par des gains de masse et de coût d'abord sur les éléments auxquels on l'applique, puis par l'effet du facteur d'amplification sur l'ensemble de la structure et le reste de l'avion : moteurs, équipements, combustible. Un tel processus suppose que la technologie dont on envisage l'application ait atteint un degré de maturation qui permette d'en prédire avec certitude les performances et les coûts.

---

1 - La nécessité d'une plus grande maîtrise des coûts [illegible] devenu au cours de la dernière décennie un des traits marquants de l'industrie aéronautique. Pour illustrer ce lieu commun il suffit de rappeler [illegible] des avions d'arme depuis 1960.

L'augmentation que l'on constate est [illegible] des performances qui s'est traduite par une complexité [illegible] plus grande qualification du personnel d'étude et de fabrication.

2 - Pour fixer un peu mieux les idées on peut schématiser la répartition [illegible] avion d'arme de la prochaine génération de la façon suivante :

Structure	36 %
Equipements (hors système d'arme)	[illegible]
Système d'arme	[illegible]
Propulsion	[illegible]

L'avionneur dont le métier est d'abord de façonner le métal [illegible] donc directement que 36 % du coût. Mais son métier est aussi [illegible] d'arme complet et c'est au niveau de l'intégration des systèmes : propulsion, systèmes d'arme, etc... qu'il peut agir sur les coûts pour réaliser un [illegible] remplisse la mission spécifiée par l'Etat-Major à un prix [illegible] prévu.

3 - C'est là le design to cost qu'on peut schématiser en [illegible] :

1) Le client exprime ses souhaits sous la forme d'une fiche programme [illegible] réduite aux performances et [illegible], et [illegible] dispose.
2) L'avionneur étudie ses demandes et propose une formule d'avion [illegible] global de coût
3) Le client et l'avionneur s'accordent sur une fiche programme [illegible] spécification prototypes, [illegible] prix [illegible] des performances et [illegible] coût
4) L'avionneur étudie, fabrique, essaye et [illegible]
5) L'avionneur et le client [illegible] contrat de série.

[illegible] conception que se détermine [illegible] performances et les prix [illegible] déterminé à [illegible] dépenses [illegible] figure [illegible].

4 - L'avionneur doit donc disposer à ce stade d'un moyen raisonnablement précis et fiable d'estimer les coûts d'un avion qu'il produira cinq à dix ans plus tard, et comme il s'agit de compromis il faut que cet outil permette de comparer des technologies différentes et en particulier celles d'aujourd'hui avec celles de demain, c'est-à-dire d'une part les technologies utilisées couramment dans la production des avions sortant de chaine et d'autre part, les technologies nouvelles qui seront utilisées quand sortira l'avion dont il veut optimiser la formule.

L'amélioration des performances par l'introduction des technologies nouvelles a toujours été une caractéristique de l'industrie aéronautique et mon propos est de montrer que si leur mise au point a permis hier une amélioration spectaculaire des performances, elle peut permettre aussi demain d'agir sur les prix de façon non moins spectaculaire. Ceci est d'ailleurs un autre lieu commun dans le domaine des produits commerciaux (figure 2).

5 - Notre métier d'avionneur consiste entre autre à concevoir une cellule dont la résistance soit obtenue pour une masse aussi faible que possible. Il ne s'agit pas seulement de réduire ainsi la masse de la cellule : au stade projet, les dimensions de l'avion, de ses systèmes, de ses équipements, de ses moteurs, sont susceptibles de varier justement en fonction de la masse au décollage et on peut dire que l'avion est encore en caoutchouc. Tout kilo gagné sur la cellule se traduit par une réduction deux à trois fois plus grande de la masse au décollage. C'est le facteur d'amplification bien connu : il suffit de regarder la répartition de la masse à vide d'un avion moderne bimoteur :

Structure	49 %
Equipements (hors système d'arme)	16 %
Système d'arme	9 %
Propulsion	26 %

A ce stade un gain de masse sur la structure s'il ne change pas le système d'arme, permet par contre de réduire le dimensionnement des équipements ainsi que la poussée du moteur et par conséquent les masses et encombrements correspondants. Ceci conduit à réduire à son tour les dimensions de la cellule et entraîne un nouveau gain de masse....

6 - Mais des réductions de masses ou de performances réagissent à leur tour sur les coûts: en matière de cellule, la masse est en effet un des facteurs essentiels du coût : le nombre d'heures de travail par kilo de structure est une fonction bien déterminée de la masse pour une technologie donnée.

De même, pour les moteurs, la poussée est l'un des principaux paramètres du coût et la réduction se traduit par une diminution du prix. Enfin, les équipements de la cellule suivent des lois du même genre en fonction de leurs performances caractéristiques.

Dès lors, si l'on veut se fixer un taux d'échange pour la cellule c'est-à-dire le prix que l'on consent à payer pour gagner un kilo, il faut au stade projet commencer à raisonner à prix et performances constants en tenant compte du facteur d'amplification. Si ce dernier est égal à 2 par exemple le taux d'échange sera le double du prix au kilo de l'avion équipé.

7 - Si on se place dans une certaine technologie, on sait établir le coût d'un élément de structure en fonction de sa masse, c'est-à-dire de son dessin dont on peut accepter le raffinement jusqu'au moment où son coût devient trop élevé en considération du taux d'échange (figure 3).

Dans le diagramme masse-coût, c'est le point de la courbe caractéristique de la technologie où la pente de la tangente est égale au taux d'échange.

Et si l'on change de technologie - en particulier pour en venir à une technologie nouvelle, on sait déterminer une courbe caractéristique et le point où il faut se placer en tenant compte du taux d'échange.

On peut très bien alors se trouver dans le cas où une technologie nouvelle apporte à la fois un gain de masse - ce qui est la raison première de son développement - et une réduction du coût qui donnera quelques aises dans d'autres compromis.

8 - Le problème est donc d'établir cette caractéristique masse-coût d'une technologie nouvelle avec une précision suffisante.

Cette précision varie évidemment avec la maturation de la technologie et on peut distinguer trois stades :

. le stade de l'expérimentation qui se passe en laboratoire et pendant lequel on procède à des essais de faisabilité et de résistance sur des éprouvettes qui peuvent aller jusqu'à des sous-ensembles assez complexes

2) Le stade de l'application sur un avion existant ou sur un prototype où on remplace un élément de l'avion par le même élément réalisé avec la nouvelle technologie. Les gains de masse ainsi réalisés sont modestes d'abord parce que les applications sont limitées en nombre et aussi parce que le dessin de l'élément nouveau doit respecter l'interchangeabilité de l'élément qu'il remplace.

3) Le stade de l'intégration où la nouvelle technologie est introduite dans le projet : l'architecture, voire même sa formule est alors conçue en fonction des possibilités réelles de la nouvelles technologie dont les limites ont été déterminées au stade précédent. C'est là qu'on obtient le meilleur rendement par l'effet du facteur d'amplification.

9 - Encore faut-il avoir choisi parmi les technologies en cours de développement, celle qui a le meilleur rendement sur tout l'avion, ou sur la partie d'avion auquel on veut l'appliquer : on ne cons'ruit pas une zone chaude avec les mêmes procédés qu'une zone froide et tel matériau bien adapté à une structure formant réservoir de pétrole ne s'emploie pas forcément autour du moteur.

Parmi ces diverses technologies, il en est une qui présente des performances remarquables : il s'agit des matériaux composites dont l'emploie constitue sans doute la plus grande révolution en matière de structure depuis le remplacement du bois et de la toile par les alliages d'aluminium - il y a de cela un demi-siècle.

Les gains qu'on peut en attendre sont en effet spectaculaires puisque les composites ont par rapport aux alliages d'aluminium des rigidités et résistances spécifiques de 1,[illegible] à [illegible] fois supérieures. Pour imager la comparaison on peut dire qu'avec un drapage optimisé, le composite Carbone-Epoxy est équivalent au dural avec une densité de 1,55 au lieu de 2,8 et que le Bore-Epoxy a une résistance supérieure au meilleur alliage d'aluminium et une rigidité supérieure à celle du titane avec une densité de 2 au lieu de 4,5 (figure 4).

De plus, les composites permettent de fabriquer des éléments anisotropes réalisant ainsi le vieux rêve des ingénieurs de placer la matière dans le sens des efforts.

10 - Le composite est en effet constitué de fibres extrêmement résistantes dans le sens long, le plus souvent de carbone ou de bore liées entre elles par une matrice qui, dans le cas des avions de combat jusqu'à M = 2,3 est une résine Epoxy cuite au four. Ces composites sont fournis sous forme de nappes de faible épaisseur (1.5 à 50 microns) dans lesquelles les fibres ont toutes les mêmes orientations et sont imprégnées de résine crue. On les drape les unes contre les autres en faisant varier leur orientation suivant les besoins de la résistance et on les cuit sous pression. On peut obtenir des tôles galbées d'épaisseur variable, des profilés en forme d'oméga, de L ou de C, ou des éléments plus complexes à raidisseur intégré en T, en sinus ou en grecque ou encore des caissons à coeur en nid d'abeille et même des caissons raidis par des nervures moulées en une seule opération en même temps que les peaux (figures 5 et 6).

11 - Ces composites ont suivi aux Avions Marcel DASSAULT le schéma de développement décrit plus haut. Après des études et essais en laboratoire les premières applications ont été faites en 1975 sur un gouvernail de MIRAGE III en fibre de carbone, puis en 1976 sur un empennage horizontal de MIRAGE F1 en fibre de bore. Après essais en vol, ces deux éléments ont été montés sur des avions de série pour des essais de vieillissement dans des conditions réelles d'utilisation. Les résultats obtenus ont permis de lancer en série les ailerons en carbone qui sont montés sur les MIRAGE F1 depuis 1978. Depuis cette même date, et dès le n° 1 de série, le FALCON [illegible] vole aussi avec des ailerons en carbone : il est ainsi le premier avion civil certifié par la FAA qui incorpore dans sa définition de type des éléments vitaux composites.

Parallèlement, les avions de développement du MIRAGE [illegible] étaient équipés de nombreux éléments en fibre de carbone : dérive, élevons, volets et portes de train, portes radar, trappettes d'entrée d'air, portes d'accès du fuselage, et d'un gouvernail en hybride carbone-bore. Bien entendu la série de ces avions sera livrée avec ces éléments composites. L'économie de masse par rapport aux mêmes éléments réalisés en structure métallique est en moyenne de [illegible] %.

En ce qui concerne le prototype MIRAGE [illegible], [illegible] hybride carbone-bore. [illegible]

[illegible]

12 - Ces diverses réalisations ont permis une mise au point des composites aussi bien en matière de dessin que dans le domaine de la fabrication en série et nous avons pu ainsi établir les bases du design to cost c'est-à-dire les instructions de dessin et les manuels de coûts sans lesquels on ne saurait valablement construire les modèles paramétriques de masse et de coût indispensables au stade de la conception d'un programme nouveau.

Les instructions de dessin sont réunies dans un manuel qui donne d'abord des règles générales concernant les caractéristiques des matériaux utilisés, les tolérances de fabrication, les protections, les métallisations. On trouve ensuite les règles de dimensionnement et de dessin des principaux types de structure : élémentsmonolithiques, caisson, etc... Enfin, plusieurs chapitres sont consacrés aux ferrures d'introduction des efforts concentrés qui constituent la pierre d'achoppement du dessin des composites.

La rédaction de ces instructions a constitué un gros travail pour réunir et mettre en forme l'expérience acquise. Mais le propre d'une technologie nouvelle est d'évoluer et le manuel de dessin se doit de suivre cette évolution : il est mis à jour une fois par an et ce n'est pas là la tâche la moins ardue.

Le manuel de coût a été construit par l'analyse détaillée des diverses fabrications prototype et série et par rapprochement avec des technologies voisines couramment utilisées comme les stratifiés en fibre de verre, les caissons métalliques à coeur nid d'abeille collés, les structures autoraidies. Comme pour les instructions de dessin ce manuel doit être recalé à intervalles réguliers pour tenir compte de l'accroissement de notre expérience.

13 - Pour illustrer ceci, on peut prendre l'exemple de l'aileron du F1 dont plus de 200 ont été aujourd'hui construits (figure 7) pour chaque opération de la gamme on a pu mesurer des temps de fabrication jusqu'au 100ème avion et établir la loi de décroissance des temps. Mais il fallait aller plus loin, analyser les opérations qui font le coût, étudier les perfectionnements propres à le réduire : modifications d'outillages, mécanisations, etc... et en déduire les coûts objectifs qui sont ceux auxquels on peut prétendre dans deux ans lorsque la série des MIRAGE 2000 sera en régime de croisière, ou dans un avenir plus lointain pour un avion nouveau.

Cette analyse et ces prévisions ont d'autre part permis de déterminer les facteurs principaux de coût, ce qui est la première chose à faire pour pouvoir ensuite construire des modèles paramétriques.

14 - Les principaux facteurs ainsi déterminés sont d'abord la complexité du type de structure étudié, puis pour chacun de ces types le prix de la matière première et le temps de drapage des pièces primaires.

Le carbone ou le bore sont en effet beaucoup plus chers que les métaux alors que le kilo d'alliage d'aluminium se situe vers 20 F et celui du titane vers 150 F, le carbone préimprégné est vendu aux USA à 50$/lb soit 500 F/kg. Il faut ajouter que les prix européens sont aujourd'hui nettement plus élevés pour diverses raisons sur lesquelles je ne m'étendrai pas et qui ne se ramènent pas seulement au faible volume traité aujourd'hui de ce côté de l'Atlantique.

On doit cependant s'attendre à une déduction sensible de ces prix et on peut raisonnablement espérer disposer en 1985 de carbone préimprégné à 20 $/lb soit environ 200 F/kg (figure 8).

Si l'on prend l'exemple d'une gouverne à coeur nid d'abeille on peut alors estimer que la matière première représentera environ 16 % du coût de la main d'oeuvre alors que pour une gouverne métallique classique, elle en représente [illegible] %.

15 - En ce qui concerne la main d'oeuvre, l'analyse dont il est question ci-dessus [illegible] conduit à la répartition suivante :

Caisson composite :

Pièces primaires carbone	1[illegible] %	
nid d'abeille	6 %	4[illegible] %
Ajustage et collage	2[illegible] %	
Pièces primaires métalliques	[illegible] %	[illegible] %
Assemblage et finition	[illegible] %	

Le coût de la gouverne est [illegible] dû aux pièces primaires métalliques et [illegible] assemblage sur le caisson [illegible]. Il s'agit principalement [illegible] d'attaque, les ferrures de manoeuvre et les paliers d'articulation. Leur temps de fabrication et de montage ne doit pas être très différent de ce qu'il serait pour une gouverne métallique classique.

En ce qui concerne le caisson composite son coût est sensiblement les 3/4 de celui qu'aurait le même caisson en structure métallique en raison du nombre réduit de pièces et de liaisons. C'est donc là que se fait le gain de main d'oeuvre, c'est là aussi que se fait le gain de masse : pour se donner des chiffres simples, avec notre prévision de prix de matière première, le passage aux composites permet de gagner de 20 à 30 % de la masse et de 15 à 25 % du prix (figure 9).

16 - Des analyses semblables ont pu être faites sur les divers types de structure présentés ci-dessus et dans les projets des avions de combat de la prochaine décennie que nous étudions en ce moment aux Avions Marcel DASSAULT l'architecture de la cellule a été conçue en fonction des composites qui constituent 35 à 40 % de la masse totale de la structure (figure 10).

La même structure réalisée de façon classique avec des matériaux métalliques aurait pesé 12 % de plus et la masse à vide de l'avion aurait été augmentée de 5,5 %. Mais alors pour conserver la mission de base et les performances demandées il aurait fallu augmenter la surface de la voilure et la poussée du moteur. C'est le facteur d'amplification qui conduirait à une masse à vide accrue de 11 %. (figure 11).

Il aurait fallu en outre augmenter de 4 % le pétrole emporté, ce qui aurait pesé de façon non négligeable sur le coût d'utilisation.

Les modèles paramétriques de coût permettent alors de calculer que dans ces conditions le prix de l'avion aurait été augmenté de 6 % et on vérifie bien ainsi que la technologie des composites réduit à la fois la masse et le prix des avions surtout lorsqu'on peut l'introduire dès le stade du projet dans le processus du design to cost (figure 12).

Ceci suppose comme cela a été dit plus haut un niveau de maturation de cette technologie qui permette d'envisager son application avec toutes les chances de réussite.

DETERMINATION DES COUTS ET DEPENSES EFFECTIVES

FUNDS COMMITMENTS AND EXPENDITURES

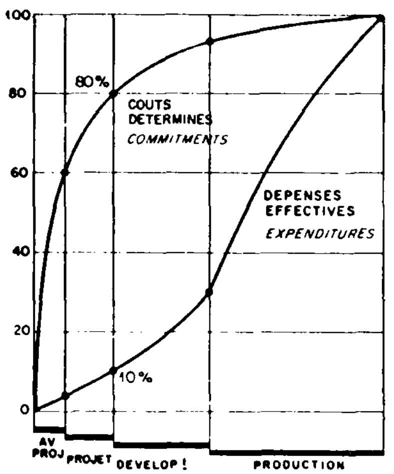
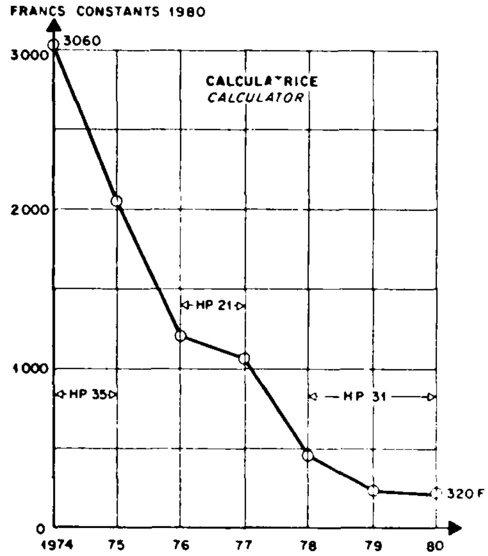


Figure 1

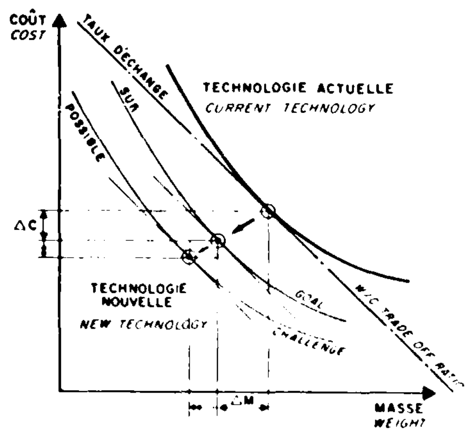
EVOLUTION DU PRIX DES PRODUITS COMMERCIAUX



TREND IN COMMERCIAL PRICES

Figure 2

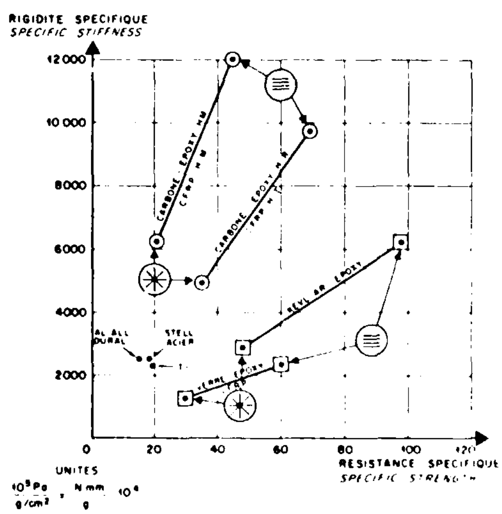
COMPROMIS MASSE - COÛT POUR LES STRUCTURES



WEIGHT - COST TRADE - OFF FOR STRUCTURES

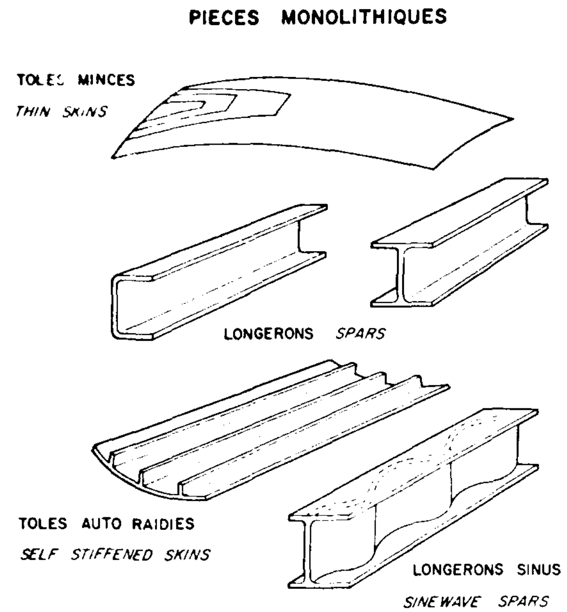
Figure 3

RESISTANCE ET RIGIDITE DES METAUX ET DES COMPOSITES



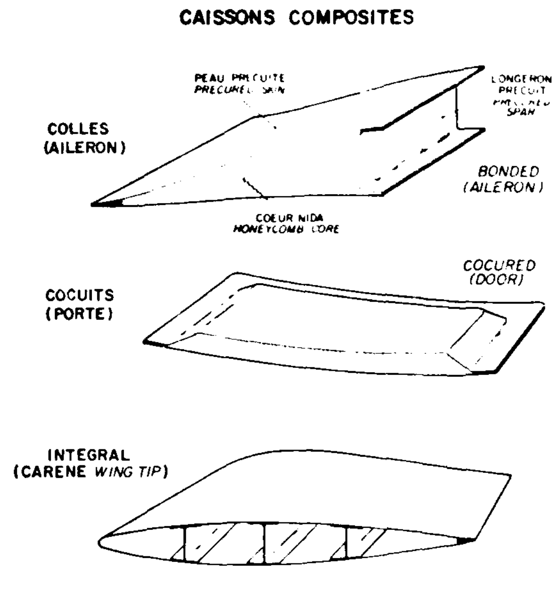
METALLIC AND COMPOSITE MATERIALS STRENGTH AND STIFFNESS

Figure 4



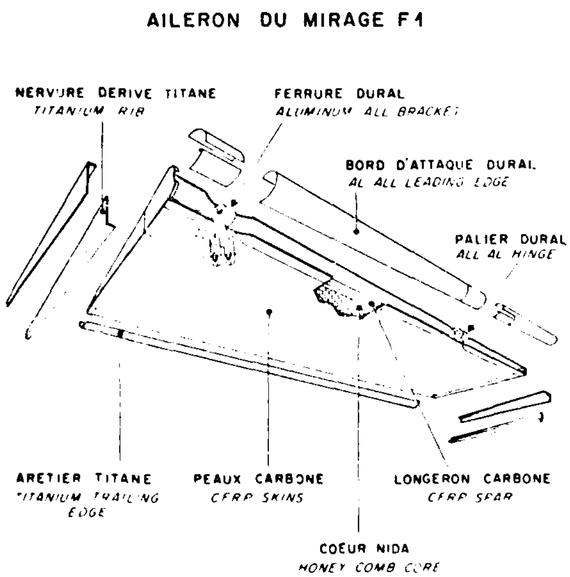
MONOLITHIC ELEMENTS

Figure 5



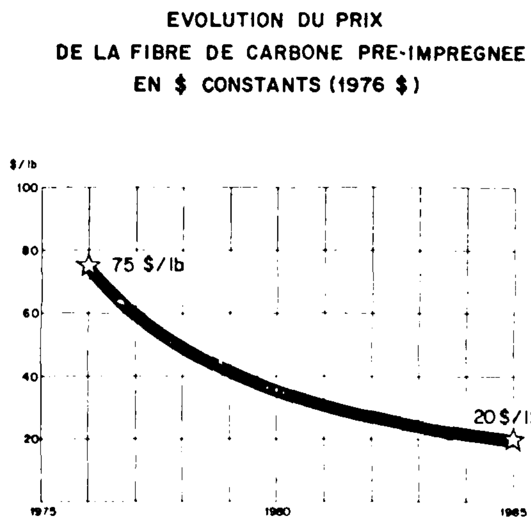
COMPOSITE BOXES

Figure 6



MIRAGE F1 AILERON

Figure 7



TREND IN GRAPHITE PREPREG PRICE

Figure 8

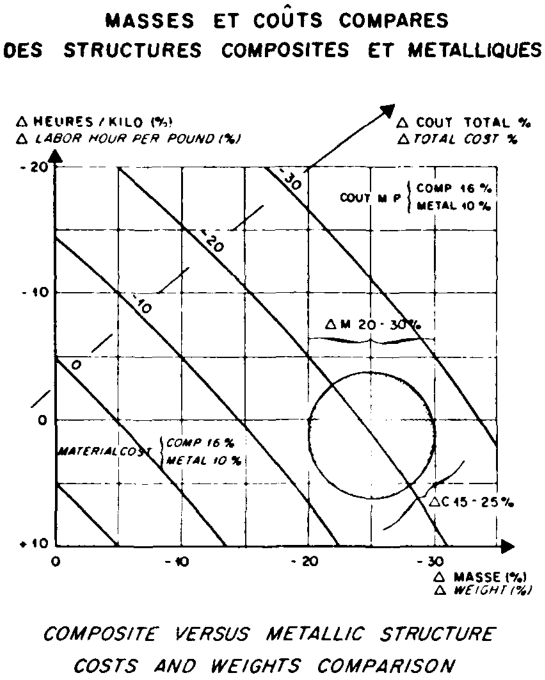


Figure 9

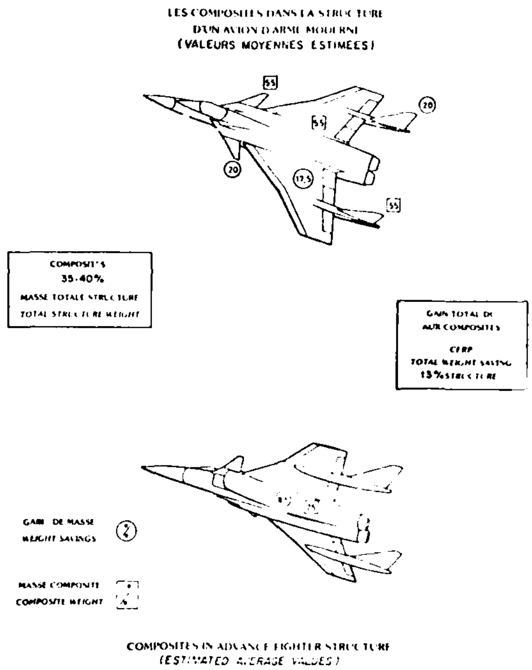


Figure 10

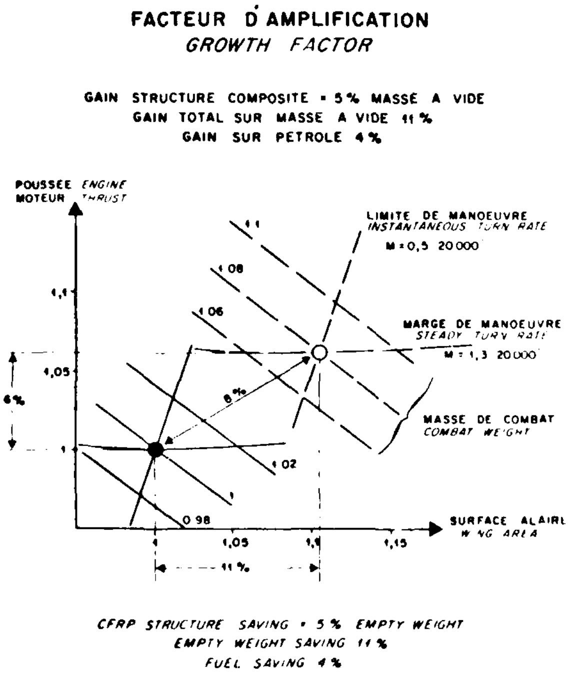


Figure 11

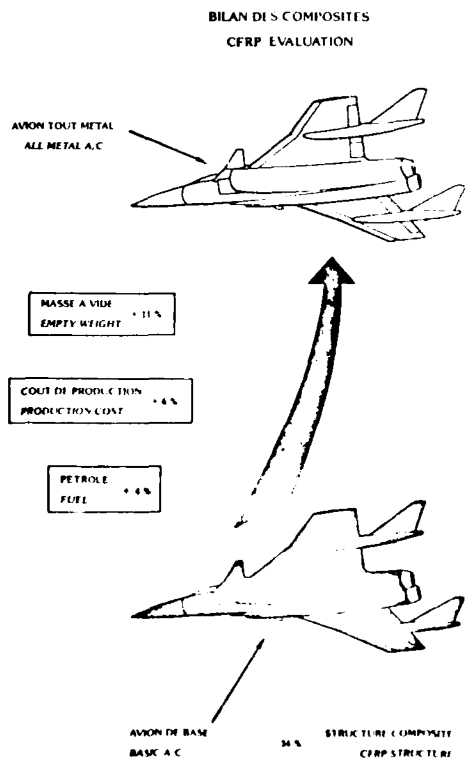


Figure 12

ORGANIZING A DESIGN-TO-COST PROGRAM

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Paris, France

Total cost control at all development and production stages is a prerequisite to any significant Design-to-Cost (D.T.C.) program. Design to Life Cycle Cost (D.T.L.C.C.) methods further require intimate knowledge of operational and maintenance costs. Specialists in this new cost management method are well aware of these two principles. Less obvious, perhaps are the great advantages to be derived through an organization specifically trained in the application of D.T.C. and D.T.L.C. principles.

The S.N.I. AEROSPATIALE Aircraft Division has been interested in this problem since 1975, and to this purpose has created a specialized organization and devised new methods for integrating costs into all phases of new programs, much in the way that weights were calculated into programs in the past.

To keep pace with this reorganization in development, emphasis has been placed on training personnel in Value Analysis and D.T.C. methods. Results of these efforts first became apparent in 1977, during development of the A 200. Today, the same principles are being applied in development of the A 310.

I - REASONS FOR APPLYING THESE NEW DEVELOPMENT METHODS

Without going into the entire history of the Civil Aviation market, it may be observed that in the past years, manufacturers have shifted their priorities from technical to economical considerations.

More than ever before, a manufacturer who wants to market a new aircraft must conform to the laws of competition.

Although he might be perfectly capable of building a good modern aircraft, this is not enough, as it would be unthinkable for two different aircraft similar in specifications to have substantially different prices. This means that there is little margin left for setting the sale price.

Furthermore, airlines are also faced with serious economic problems and are not interested only in purchasing price, but also in operational and maintenance costs, known in America as "LIFE-CYCLE-COST", an aspect to which the S.N.I.A.S. Aircraft Division has given special attention.

First, aircraft price is determined in accordance with competition levels, and then operating costs are kept in check so as not to compromise or even nullify the benefits of the operation.

Competition implies the embodiment of modern technologies which involve painstaking development work executed by highlyqualified personnel, and tests that are constantly growing in sophistication to improve safety levels.

These factors together with inflation result in aircraft development becoming exponentially more expensive.

The aircraft manufacturer is thus confronted with many such problems when developing a new aircraft.

During the initial design phase, technical specifications are established which dictate the broad lines of the project. This is followed by pre-project studies during which costs are analysed in the same way as other criteria such as weights, performance, reliability, etc...

It would be wrong to conclude from this brief summary of the groundwork preceding the production of a new aircraft, that there is no real innovation and that by simple following existing state of the art rules, such problems would solve themselves. This is not the case.

The goals can be achieved only though rigorous application of the new management methods, once personnel has been properly trained to do so.

The S.N.I.A.S. Aircraft Division is aware of this and is already applying the Design-to-Cost method which seems to hold great promise as a tool for keeping to program target costs, while at the same time respecting the other criteria to which a modern carrier must comply.

The method employed is a development of the "Design-to-Cost" program management method adopted by various American manufacturers, especially when handling certain Government contracts.

But what exactly is "DESIGN TO COST" ?

II - DESIGN-TO-COST

In 1969, the competent committees of the American Senate and House of Representatives started expressing their misgivings with regard to escalation in the cost of military programs, and commissioned the Defence Department (D.O.D.) with investigating the reasons for such budget overshooting and taking remedial action.

The investigation revealed :
6 % of price overshooting to be caused by planning variations,
25 % to be due to miscellaneous modifications called for by the D.O.D.,
16 % to be due to fluctuations in the economic situation,
56 % to be ascribable to the manufacturer, caused by such factors as : modifications, increase in the cost of spares, documentation and training.

Modifications taken as a whole (D.O.D. and manufacturer) accounted for approximately 80 % of the overprice.

Because of this state of affairs, the D.O.D. had been obliged for several years to curtail its orders so as not to exceed budgetary limits. This is tantamount to sacrificing quantity for performance, and where defence is concerned, it is evident that one cannot exist without the other. In fact, for certain weapon systems, quantity is the decisive factor.

Such considerations motivated an entirely new weapon system procurement policy, and new management methods where such programs were concerned.

Previously, when issuing Calls for Bids, D.O.D., stipulated many technical specifications to be met by manufacturers, which directly resulted in similar cost levels from one manufacturer to another, plus very expensive modifications.

The new policy, on the contrary, stipulates only minimum technical specifications, but does impose production costs.

This gives manufacturers far greater latitude in their "product" as long as it can fit in with the specified price bracket. Consequently, they must be more inventive and apply certain methods such as "Value Analysis" to obtain a more attractive product. This greatly reduces subsequent modifications.

The new policy was called "Design-to-Cost"

D.T.C. was first employed in the aerospace field in 1970 with the A.10 project (Fairchild and Northrop).

Its most recent application is in the YC 14 and YC 15 military STOL carrier program, in which development and building of two prototypes was initiated jointly by BOEING and DOUGLAS.

The sole conditions stipulated for this program were :
1 - Unit price computed for a batch of 300 aircraft ;
2 - Pressurized cockpit ;
3 - Bay volume.

III - THE S.N.I.A.S. "DESIGN-TO-COST" METHOD

This method, employed by the Helicopter Division has given excellent results with the DAUPHIN, SA 360 and ECUREUIL SA 350 helicopters. The method was also employed by SOCATA in design an production of the TB 10. But since 1976 it has perfected on the basis of what was learned during study missions to certain American firms and courses in Design-to-Cost taken at George Washington University.

1 - Basic principles

- Training personnel to Design-to-Cost methods and "Value Analysis".

- One single Program Manager in charge (performance, costs, deadlines).

- Evaluation of program financial factors, especially Life Cycle Cost and the production cost to be adopted as "Aircraft Target Estimate".

- Breakdown of work into individual jobs and determining their purpose and costs (in constant indexed Francs with reference to TOP program).

- Organization of operational DEVELOPMENT/PRODUCTION teams for job analysis.

Example : Level	1	Cost of	program.
	2	" "	aircraft-Aircraft Target Estimate.
	3	" "	structure ans systems.
	4	" "	assemblies (e.g. fuselage sections).
	5	" "	subassemblies.

- Choice between alternative conceptions to obtain best cost-performance ratio.

- Organizing production for cost verification and check against Target cost.

Without going into the above paragraphs in detail, it is stressed that many advantages are to be obtained through this new method of organizing individual operational teams at development phase.

Each team is made up of development and production engineers, procurement and quality control experts, management and estimate engineers and administrative executives.

Each member remains attached to his original department and each team is able to draw upon the experience and work of that department. Conversely, the department benefits by the analyses and conclusions of the team.

With one man in charge, each team analyses given jobs, each having its own target cost, while team members are interchanged as the development program advances.

Conditional to proper application of the D.T.C. method is the training of personnel, which takes the form of one seminar per month dispensed to 25 persons representing the departments involved in the program. Since 1976, 400 persons have taken part in these seminars.

2 - Development stages

Any new project involves several phases, the first usually being determinant, as it is at this point that technical objectives and realistic costs must be established, analysing the functions and costs of previous productions to identify factors subjet to overcost.

- Functions are then analysed at all phases, from assemblies to major components.

- Different solutions are then compared for each function and the cost of each is analysed in accordance with available production facilities.

Such evaluation involves the use of such factors as :
- statistical data bank for production times,
- parametrical studies of structure and system costs, etc.

- Selecting the best compromise in each case between performance, production costs and maintenance.

- Making a final breakdown of the target estimate while incorporating optimum production distribution.

Maintenance is treated in a separate study to arrive at the Life Cycle Cost concept.

To do this, it is necessary to collate the following data from the airlines :

- type of maintenance planned,
- rate of unwarranted equipment removal,
- percentage of equipment returned to supplier,
- method of computation employed for Direct Operating Cost (D.O.C.) T.B.O. Mean Time Between Overhauls (M.T.B.O.) - Mean Time Between Failure (M.T.B.F.) and Mean Time Between Removal (M.T.B.R.)
- policy of structural and equipment spares, etc.

Life Cycle Cost demands close collaboration between airline and manufacturer, especially for establishing maintenance cost models which serve as a basis for selecting equipment and locating it within the structure.

The second phase of the project consists in distributing development execution among different Development/Production teams. Each team sees to its own portion of the aircraft while harmonizing action to the general lines of the project.

This includes :

- Establishing technical procedures covering the selected principles and interface specifications as well as specifications covering equipment.

- Subdividing production into the shorted possible cycles giving the best overall cost, together with the corresponding schedule.

Figure 1

Determining the target cost of each job fraction in accordance with "Aircraft Target Cost Estimate".

Figure 2

The third phase involves the preparation of production blueprints by each operational team in accordance with the schedule planned at phase 2.

Each unit conception which is arrived at through addition of its component jobs is represented by a cost evaluation compared to target cost.

This evaluation takes into account such parameters as :

- cost manual,
- quick cost lists,
- semi-equipment file,
- statistics on production times.

Figure 3

If necessary, design is reconsidered to comply with targets.

Figure 4

All costs are entered and followed on a general file. Tooling and production methods are established simultaneously.

Figure 5

The first units are then built in the workshop to verify that they comply with targets.

CONCLUSION

Upon first glance, it might appear that there is nothing very new in the Design-to-Cost method, as manufacturers have always been faced with sale price and cost price problems.

But in fact, it does offer new solutions to old problems.

In the field of Aeronautics, this is the first time that a method has been employed for cost management in the way traditionally reserved for weight computation.

Aside from the analytic aspect and the systematic search for individual costs at each stage of the project, it favors improved collaboration among the different departments working on the program.

It furthermore results in Value Analysis studies right from project stage, which is an added garantee that the right solutions will be chosen.

Moreover, the need to consider operational and maintenance costs deters the manufacturer from his tendency to weigh his own immediate advantage only, overlooking that of the operator, although, to be sure the establishment of any valid Life Cycle Cost requires very close collaboration with the airline.

Figure 6 - Figure 7 - Figure 8

The new A 200 aircraft has been developed by applying D.T.C., and results are remarkable.

Several examples of Value Analysis studies concerning structural components of this aircraft have been appended. Figure 9 - Figure 10.

AIRBUS B 10 studies (A 310 studies have employed the same principles from the outset and it has been seen that they ensure optimization of the various parameters that a new aircraft should embody to be competitive.

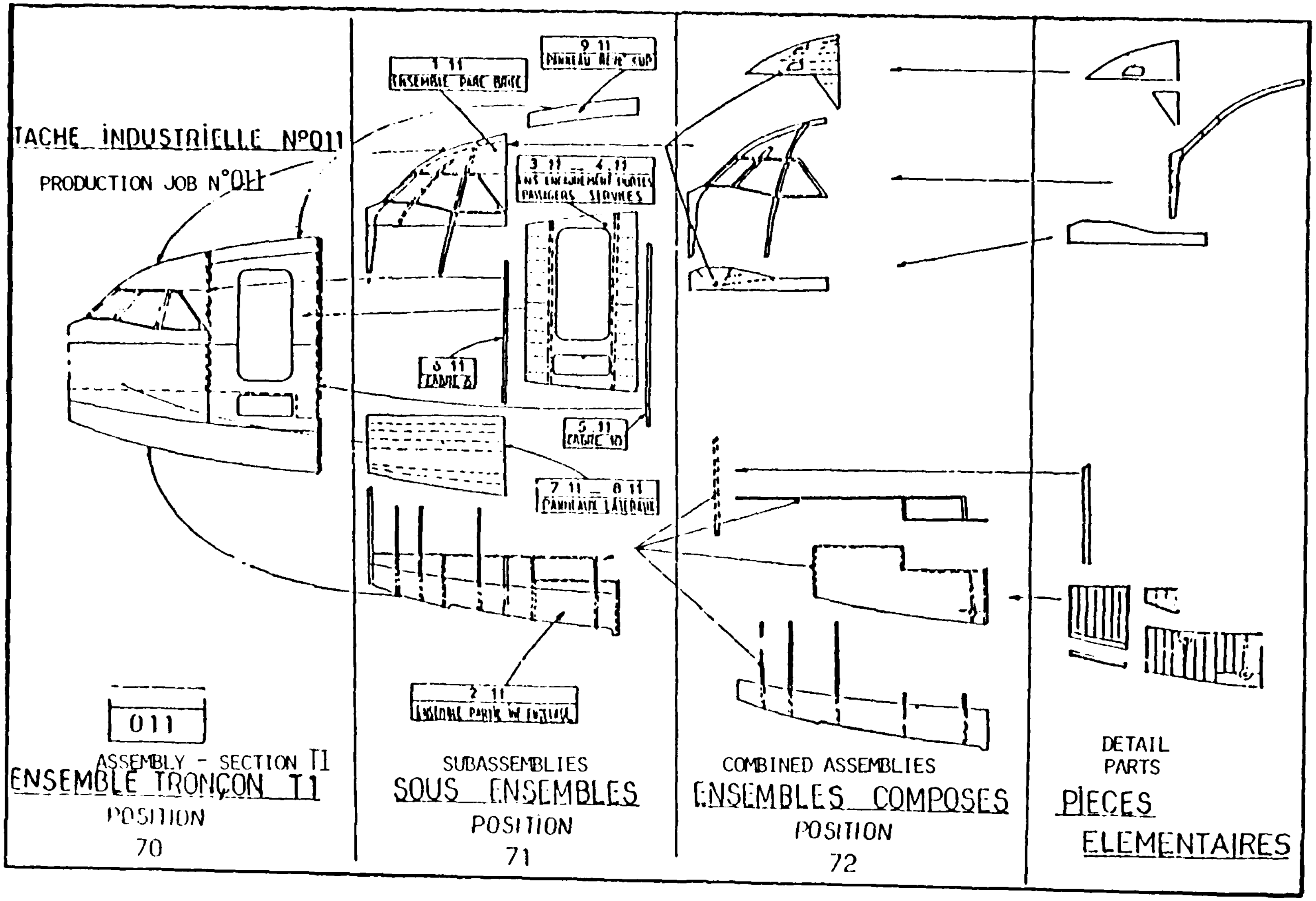


Fig.1 Job breakdown on Section T1

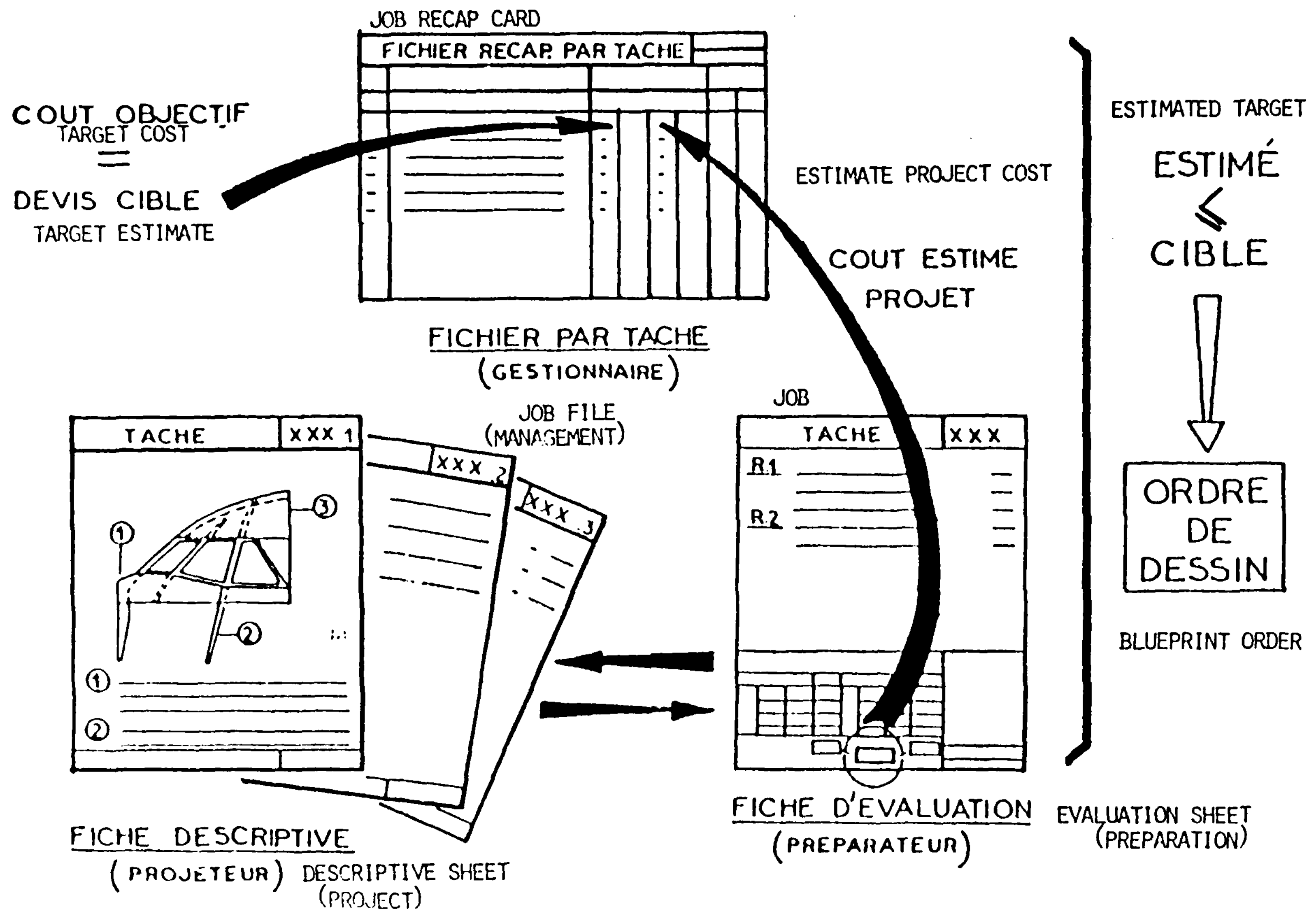


Fig.2 Project cost estimate

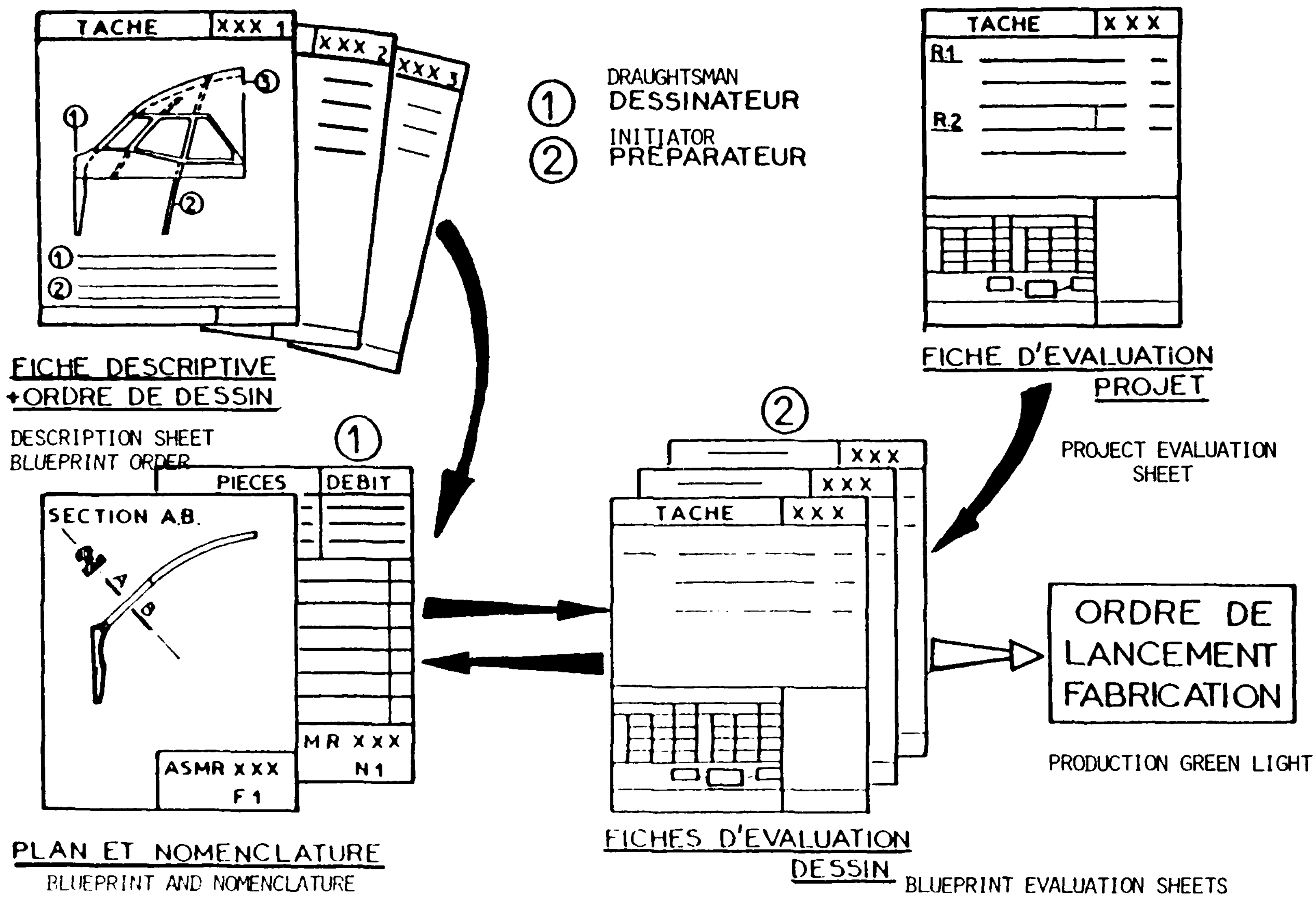


Fig.3 Estimate of blueprint costs

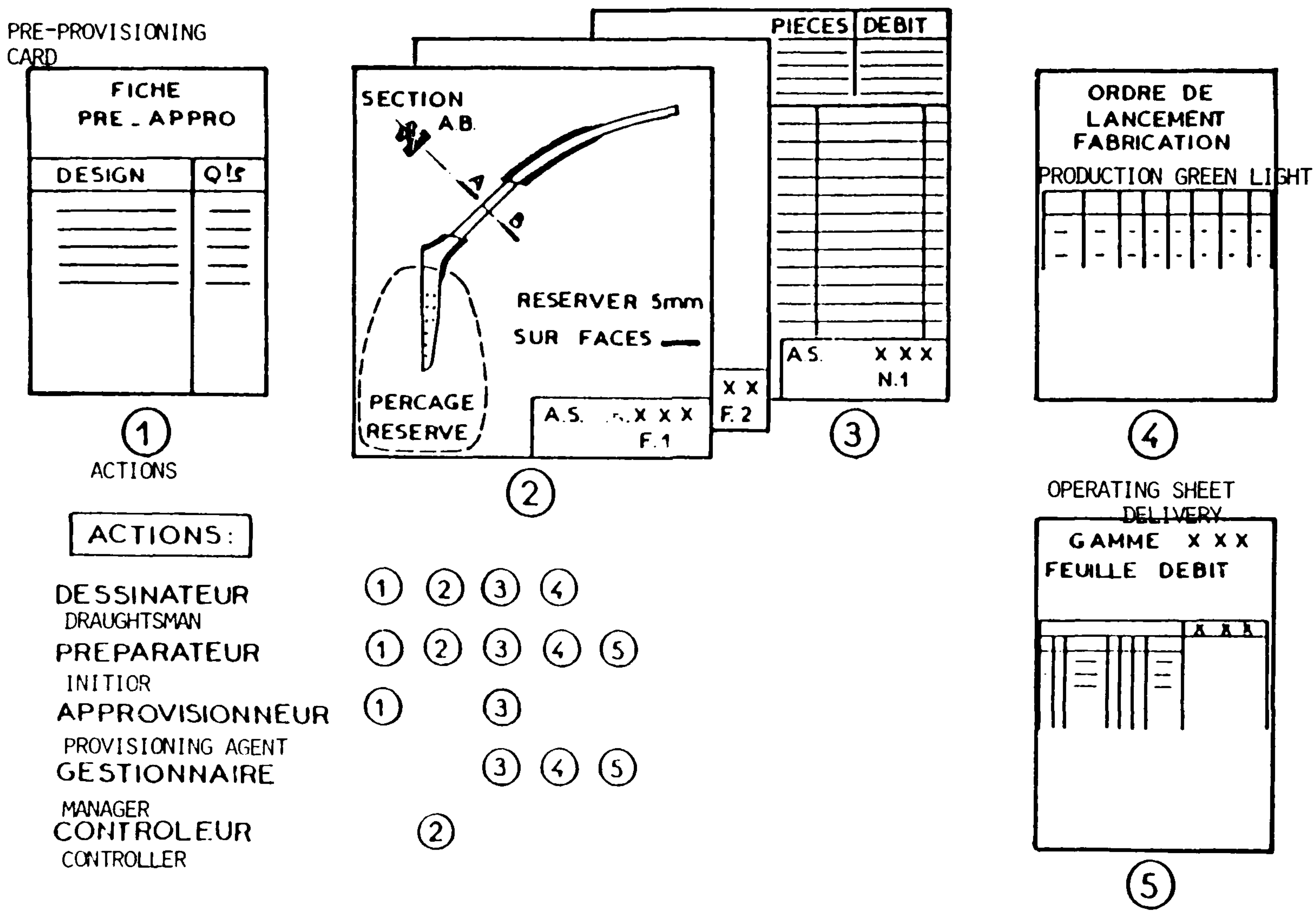


Fig.4 Manufacturing of initial parts

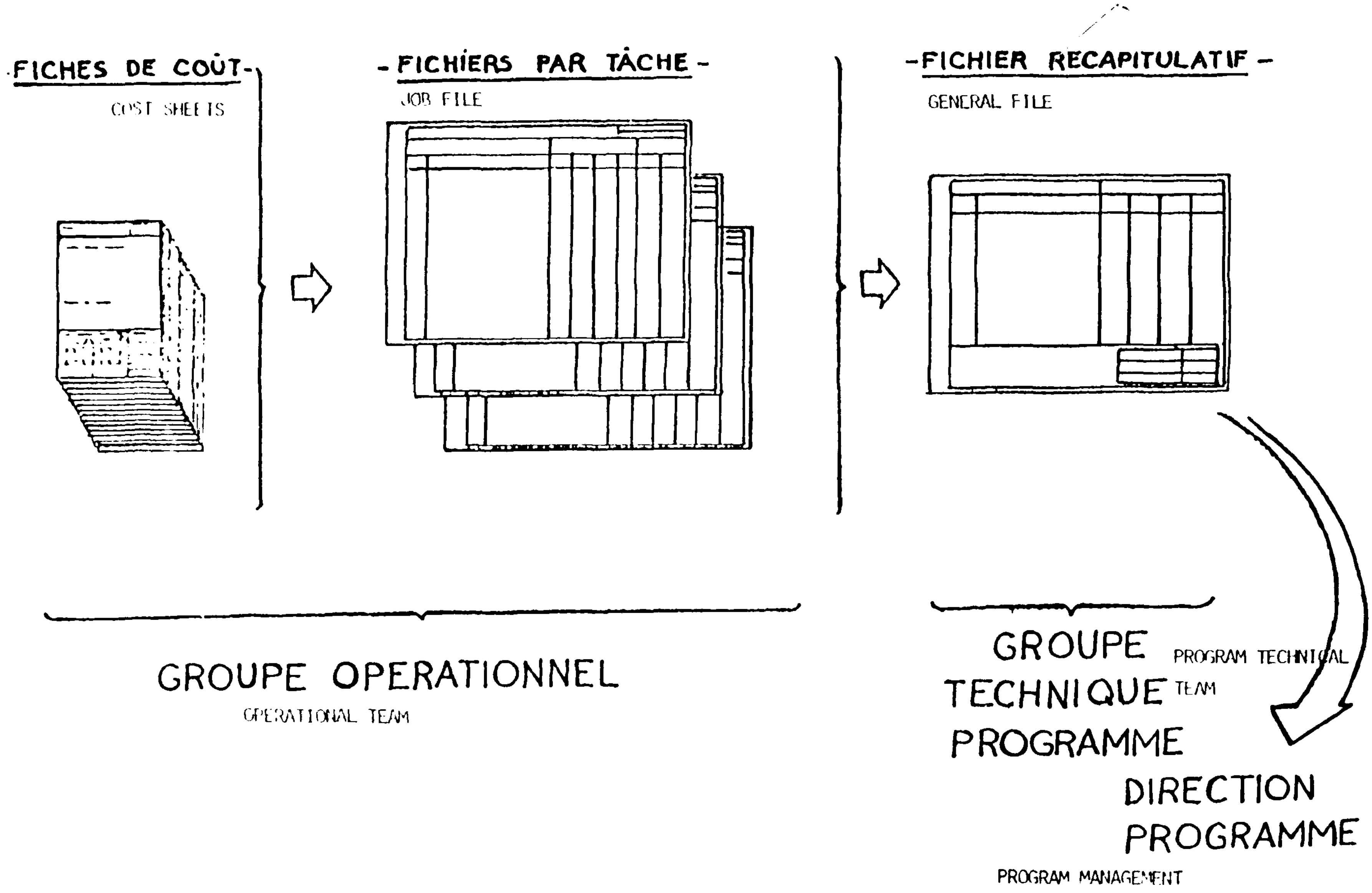
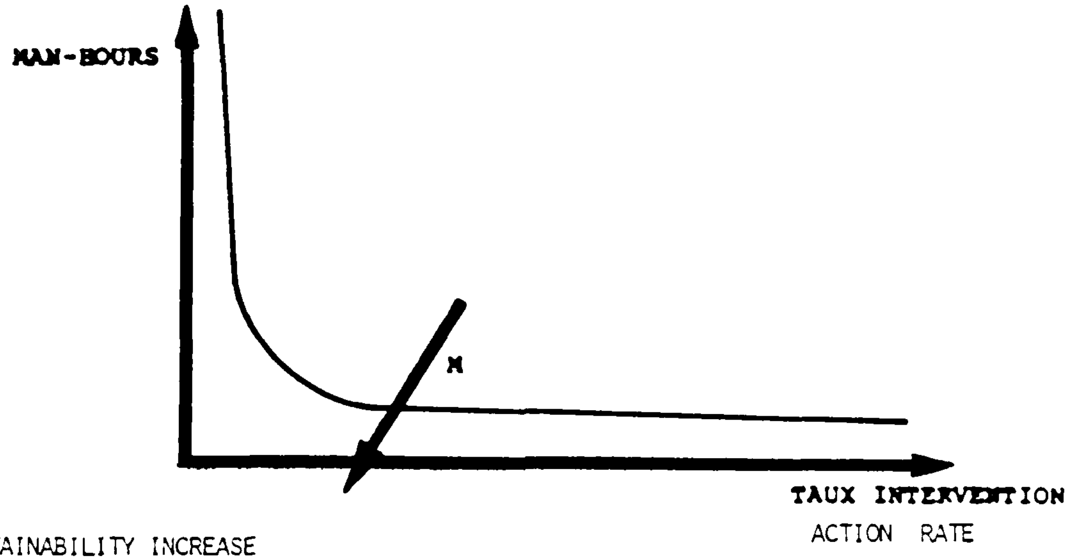
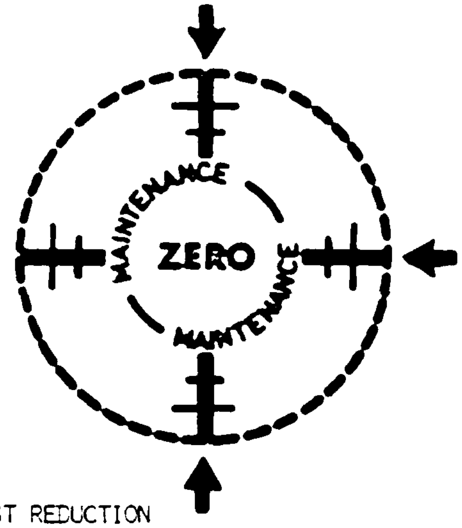


Fig 5 Cost control



MAINTAINABILITY INCREASE
Accroissement maintenabilité



SUPPORT TO COMPANIES
Support aux compagnies

- DOCUMENTATION
- FIELD SERVICE
- B.S.

COST REDUCTION
Réduction des coûts

SPARES (CONSUMPTION, PRICE, COMMONALITY)
- RECHANGES (CONSOMMATION, PRIX, COMMUNALITE)

GROUND EQUIPMENT (MAIN BASE/INTERMEDIATE STOPS)
- OUTILLAGES AU SOL (MAIN BASE/ESCALES)

- CK/LIST

BY EXTENSION MAINTAINABILITY
PAR EXTENSION **MAINTENABILITE** =

RULES FOR ESTABLISHING MAINTENANCE POLICY
REGLES DE CONCEPTION D'UNE BONNE MAINTENANCE

Fig 6 Maintenance

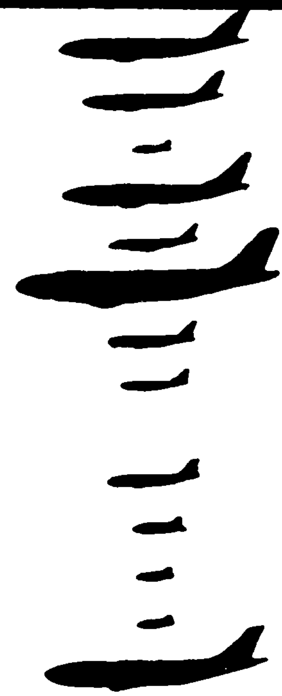
GIVE MAINTENANCE COSTS TO DESIGN OFFICE, TO PRODUCTION OFFICE, WHICH ARE
DONNER DES CHIFFRAGES/MAINTENANCE AU B.E., A LA PRODUCTION QUI SONT
INTEGRATED INTO FINAL PROBLEM : COST
INTEGRES AU PROBLEME FINAL : .... LE COUT

ORDRE OF MAGNITUDE
Ordre de grandeur

D.O.C. FOR ONE AIRCRAFT **POUR UN AVION**	/ COST **COUT 15 M$**	D.M.C. /YEAR **3000 HR/AN** 1976

D.O.C. DISTRIBUTION — OVER AIRCRAFT LIFE

REPARTITION D.O.C.	$/HR	SUR LA VIE AVION
AMORTIZATION (14 YEARS) **AMORTISSEMENT (14 ANS)**		
INTERESTS **INTERETS**		
INSURANCE **ASSURANCE**		
TECHNICAL CREW **EQUIPAGE TECHNIQUE**		
COMMERCIAL CREW **EQUIPAGE COMMERCIAL**		
FUEL **CARBURANT**		
LANDING DUTIES **TAXES ATTERRISSAGE**		
FLYING DUTIES **NAVIGATION**		
MAINTENANCE **MAINTENANCE**		
AIRFRAME LABOR **M.O. CELLULE**		
SPARES **RECH.**		
ENGINE LABOR **M.O. MOTEUR**		
SPARES **RECH.**		
DMC MAINTENANCE TOTAL **DMC = TOTAL MAINTENANCE**		
D.O.C. OPERATING COST **D.O.C. = COUT EXPLOITATION**	2125	5,70 A 6,6
	2200 $ HR	600



PROFITS
Benefices (U.S.)

2 TO 3 % OF D.O.C.
2 A 3% DU DOC

I.E. APPROXIMATELY $ 60/FLYING HOUR
SOIT ENVIRON 60 $ /HVOL

Fig. 7 Sensitizing to operating cost

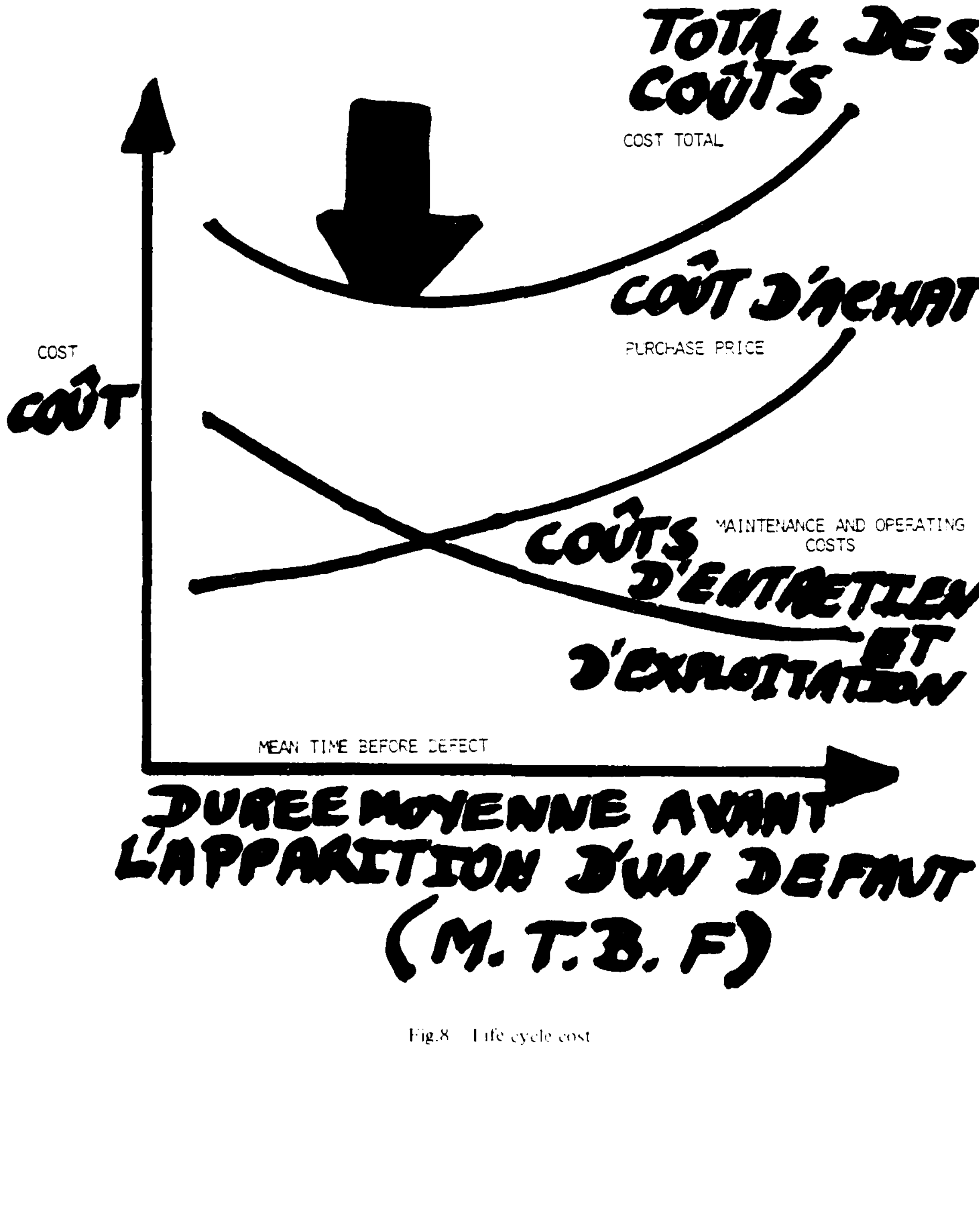


Fig.8 Life cycle cost

DESIGNATION	TECHNICAL CONSIDERATIONS		WEIGHTS	COST ANALYSIS			MAINTENANCE
	ADVANTAGES	DRAWBACKS		FAVORABLE	UNFAVORABLE	RATING	
RIB ATTACHED TO SKIN (SHEETS + STRINGERS)	FAIL-SAFE ENSURED : SEPARATE WEBS AND FLANGES PLUS MULTIPLE ATTACHMENT TO SKIN. WEB AND FLANGE CARACTERISTICS ADOPTED TO THEIR FUNCTION.	MULTIPLE DRILLING IN SKIN (SEALING)	3,9 KG (AVERAGE RIB)		GREAT NUMBER OF PARTS. BOX STRUCTURE ASSEMBLY TIME FAIRLY LONG.	1,27	CONVENTIONAL REPAIR
RIB NOT ATTACHED TO SKIN (SHEETS + STRINGERS)	FAIL-SAFE ENSURED : SEPARATE WEBS AND FLANGES.	ATTACHMENT OF RIBS TO STRINGER INNER FLANGES : NO AEROSPATIALE EXPERIENCE GAINED IN THIS FIELD.	4 KG (AVERAGE RIB)	EASY ASSEMBLY AND MATCHING DURING ASSEMBLY (SETTING CAPABILITY).	DOES NOT APPLY TO AN INTEGRAL SKIN.	1	CONVENTIONAL REPAIR
ALTERNATE WITH ATTACHMENT TO STRINGERS WITH DOUTLER	-IDEM-		4,2 KG (AVERAGE RIB)	EASY MATCHING	GREATER NUMBER OF PARTS.	1,04	CONVENTIONAL REPAIR

Figure

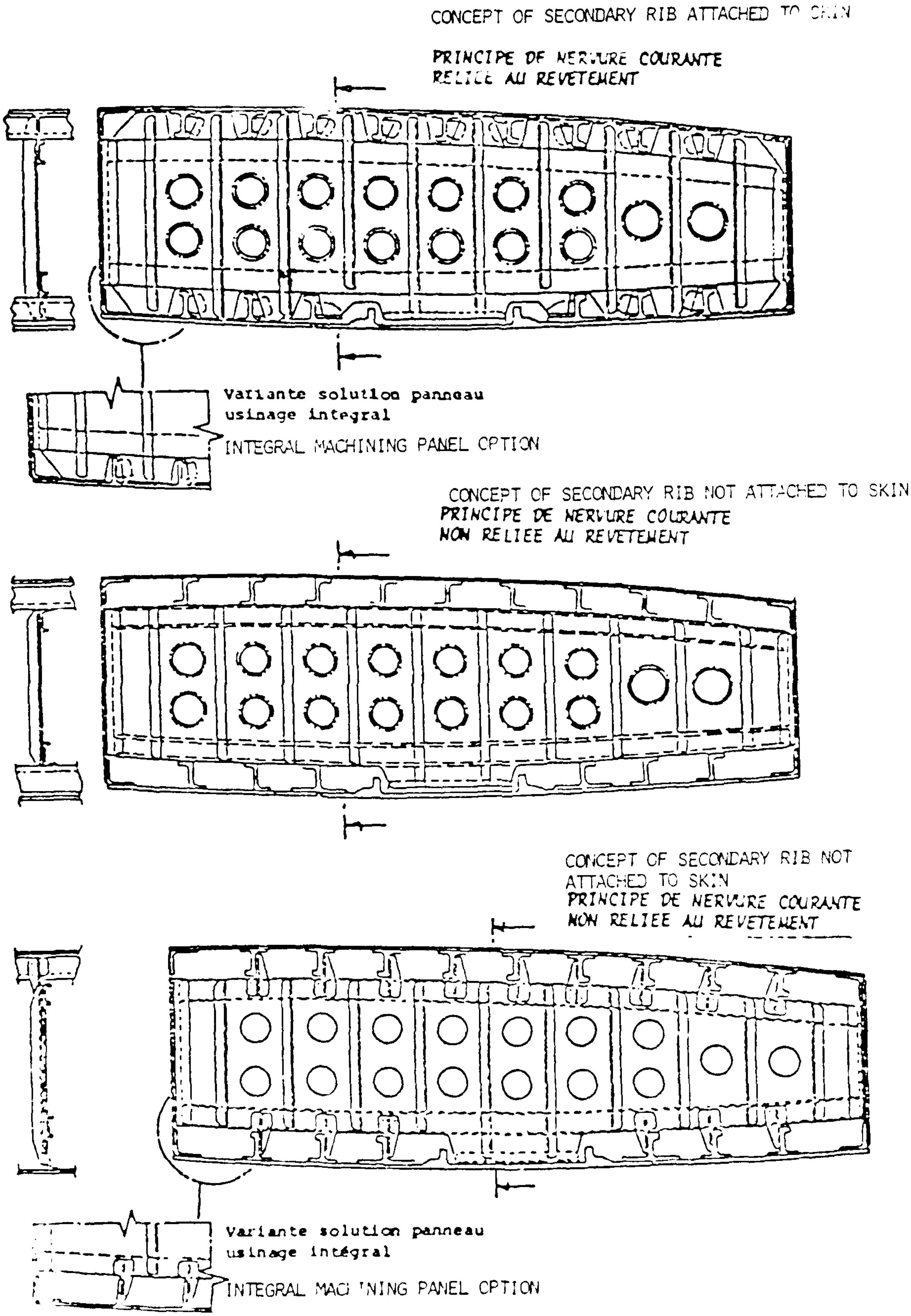

CONCEPT OF SECONDARY RIB ATTACHED
PRINCIPE DE NERVURE COURANTE
RELIEE AU REVETEMENT
Variante solution panneau
usinage integral
INTEGRAL MACHINING PANEL OPTION
CONCEPT OF SECONDARY RIB NOT ATTACHED TO SKIN
PRINCIPE DE NERVURE COURANTE
NON RELIEE AU REVETEMENT
CONCEPT OF SECONDARY RIB NOT
ATTACHED TO SKIN
PRINCIPE DE NERVURE COURANTE
NON RELIEE AU REVETEMENT
Variante solution panneau
usinage intégral
INTEGRAL MACHINING PANEL OPTION

Figure 10

A New Method for Estimating Transport Aircraft Direct Operating Costs

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U.S.A.

SUMMARY

The introduction of gas turbine powered aircraft into airline service demonstrated that methods used to estimate in-service direct operating costs for piston engine powered aircraft were no longer valid. In addition, changes in product reliability and maintainability produced support cost patterns that were much different than had been previously experienced.

As a means of assisting the airlines to estimate relative direct operating costs for new gas turbine powered airplanes, a fairly simple methodology was developed by the Air Transport Association of America. However, the value of this methodology for estimating these costs for transport aircraft that were still at the design stage became increasingly suspect as changing technology necessitated its frequent updating with new coefficients to reflect current airline experience.

It thus became necessary to develop a means of estimating aircraft direct operating costs for comparative purposes that was able to recognize and include the potential benefits that could be gained from new technology and design innovation when applied to commercial transport aircraft.

The work performed on this subject by American Airlines under NASA contract, with the Boeing Company and Pratt & Whitney as sub-contractors, is reviewed. The validity of the developed new methods and how they can be used in the evaluation of new aircraft for an airline's fleet is also demonstrated.

INTRODUCTION

The first universally recognized method for estimating commercial aircraft direct operating costs was published by the Air Transport Association of America in 1944. This methodology, developed from a paper (1)* published earlier in 1940, was based on statistical data obtained from airline operation of DC3 airplanes. Extrapolation to encompass the direct operating costs of larger piston engined aircraft and frequent revision (1949, 1955, 1960, and 1967) to recognize the rising costs of airplanes, labor, material, and fuel (sound familiar?), plus the introduction of, and experience gained from, turbo-prop and turbo-jet transports enabled a somewhat after-the-fact awareness of direct operating costs that could be envisaged for a particular type of aircraft in airline service.

A standard method for estimating airline indirect operating expenses was proposed by Boeing and Lockheed in 1964 for the Supersonic Transport and updated versions were introduced by Lockheed in 1966 (2) and 1970 (3) but never gained widespread recognition. Like its ATA brother, it too, began requiring revision to reflect the effects of inflation and changing technology.

U. S. airline dissatisfaction with the outdated ATA methodology (the ATA method was not sensitive to things that generated cost, e.g., gas path temperatures, and was overly sensitive to things that did not necessarily have a major cost impact, e.g., thrust) caused NASA to fund two study programs to develop new methodologies that would, in the commercial airline environment, provide valid operating cost comparisons between current and future technology for:

1) Propulsion systems
2) Airframe systems and Aircraft related direct operating costs.

American Airlines was fortunate in being the prime contractor for both NASA study programs with Pratt & Whitney as a subcontractor on Item 1 and the Boeing Company as sub-contractor on Items 1 and 2.

*Numbers in Parentheses Designate Reference at End of Paper

It is worthwhile stressing at this point that the operating costs generated by the new methodologies are for comparative purposes only and <u>cannot</u> be considered in absolute terms. Wide variations between airlines in management philosophy, accounting practices, aircraft utilization, etc., prevent the model from being truly representative of a specific airline. However, by periodic analysis of its own historical data, each airline can determine for itself the relative importance of each cost factor and modify the basic models accordingly.

Inputs to the study programs are illustrated in Figure 1. The objectives of the work were to obtain a better understanding of airline operating costs and, by analysis, develop a more complete and detailed aircraft related operating cost model. The data base consisted of 1960 through 1972 airline experience for the propulsion study and 1974 and 1975 airline experience for the airframe study. However, data from as far back as 1958 was available on specific subjects, although on occasion, detail was less concise. The results of these studies were released in 1974 (4) and 1978 (5).

DISCUSSION

Individual costs were examined and their relative importance for a typical aircraft (DC10-10) in 1980 are shown in Figure 2. These include airframe and propulsion system maintenance, flight crew, spares investment, flight attendants, aircraft service, landing fees, insurance, depreciation, and fuel elements. For comparison with the standard ATA model, the costs studied here, included all of the ATA system costs, plus flight attendants, aircraft service, landing fees, and control fees. However, most of the effort was concentrated in looking at the detailed maintenance cost breakdown for each engine module and airframe system.

MAINTENANCE COSTS

The ATA model breaks maintenance system cost only into labor and material costs (Figure 2) for the entire airframe and the entire engine (plus an allowance for overhead burden which includes supervision and inspection costs). Like other cost estimating relationships in the ATA model (Table I), airframe maintenance cost is expressed essentially as a function of airframe weight, first cost and labor. In contrast, the present models (Tables II, IIA & III) compute comparative labor and and material maintenance costs for each engine module and airframe system as a function of the design characteristics of the system. In addition, by using the present model, the relative importance of the various engine module and airframe system maintenance costs can be determined if certain design specifications of the study aircraft and/or engine are known.

Again, it should be stressed that these methodologies are only valuable for determining comparative operating costs for aircraft and propulsion systems. Although the result of exercising these methodologies demonstrates excellent sensitivity to technological changes, they are insensitive to the wide variations found between airlines in management attitudes and philosophy, operations, maintenance, and accounting practices, etc.

The propulsion study confirmed almost without exception, and without regard to military heritage, that each new engine design introduced into airline service developed a basic expense pattern similar to that exhibited in Figure 3.

In the first years of ownership, maintenance costs were relatively low because of newness and design changes made prior to production to preclude early failure modes highlighted in the engine development program. However, a peak cost level occurred in the 2nd and 3rd years of ownership after which, as a result of other design corrective action programs and change in maintenance techniques, costs steadily declined until a mature level was reached about 7 years after introduction. These mature costs occurred at a magnitude less than half that of the peak cost and are even lower (in terms of constant year dollars) than the costs encountered when the engines were new. Derivative and follow-on models of the engines benefit from this experience and follow the same general trend of low initial cost to peak several years later at or close to the mature cost of the early engine models.

The study also revealed the major cost determinant for gas turbine engines, regardless of technology level, was gas path temperature and its effect, in particular, on the hot section of the engine. It is this section of the engine, expensive in material costs by the use of metals capable of withstanding the excessive temperatures found therein, that provides the major impetus to engine reliability, life, and operating expense.

A classic example of the influence of engine hot section gas temperature on the distribution of engine maintenance material costs by engine module is provided in Figure 4. An early technology, low by-pass, low combustor temperature engine is compared to a more fuel-efficient, high by-pass, high combustor temperature and more advanced technology engine. Not only are the cost levels higher for the more advanced technology engine, but a higher portion of the expense is in the hot section of the engine.

It is therefore necessary to ensure changes in engine design and technology that may be introduced during these trying days of rapidly increasing fuel prices to reduce specific fuel consumption do not have an adverse effect on engine maintenance costs. The use of

exotic materials to permit increases in gas path temperatures may also result in maintenance material expenditures in excess of the fuel savings derived from an improvement in specific fuel consumption (SFC).

Figure 5 highlights how improved packaging of the engine in its nacelle can also improve maintenance costs. Again, improvements sought here must be weighed against the nacelle design and requirements that could lead to an increase in drag and, hence, fuel burn.

An example of the data correlations made for each of the 26 airframe systems is given in Figure 6 for the landing gear system. Labor and material cost per trip (2.5 hour average flight length) is given for the entire domestic fleet. Good correlation between cost and maximum taxi weight is obtained both for the entire landing gear system (gear, tires, and brakes) and also for only the gear and tires. In addition to maximum taxi weight, other correlation parameters were tried (e.g., number of wheels, landing energy and approach speed) and correlation of these with cost met with varying degrees of success. Since good correlation was obtained with this simple weight parameter, it was selected for use in the final cost model. The equations developed from such correlations for each of the propulsion and airframe systems and summarized in Tables II, IIA, III, and V provide representative trip costs. Tables VI and VII show how many individual aircraft and propulsion systems specifications must be known in order to use these maintenance cost relationships as compared with those of the ATA model. Correlating parameters used are based on the known physical characteristics of the airplane whenever possible.

The data showing the relative importance of various airframe costs for different aircraft (Figure 7) indicate that landing gear is the single most important airframe maintenance cost for the first generation jets such as the Boeing 707 and the Boeing 727. This cost, although substantially higher than for first generation jets, was reduced to being the fourth most important cost on second generation wide body jets such as the Boeing 747 and DC10. This is probably because of improved tire and brake technology and also better airline maintenance techniques (Figures 8 & 9). Major improvements in maintenance costs come from the very dramatic increase in the time interval between major inspections as airlines and regulatory agencies gain additional confidence in specific aircraft and as airlines develop improved repair methods over a long period of time. Nevertheless, inspections and miscellaneous costs remain very high for the original narrow body jets (as they also do for the newer wide body aircraft). Equipment and furnishings are also a leading airframe maintenance cost item, as is the auxiliary power unit (which was not used on some of the first generation jets). These four systems, together with the navigation system, generally account for over 50% of the total airframe maintenance cost (Figure 7). The high cost of the auxiliary power unit (together with reliability problems sometimes associated with this equipment) often leads airlines to urge designers to consider this unit as another engine which should ideally meet the performance and reliability standards demanded of the basic engine.

Just as an airplane manufacturer experiences a production cost learning curve as more and more copies of a new airplane are fabricated, an airline experiences a maintenance cost learning curve when introducing a new technology aircraft. To a large extent, this is a result of learning how to do many individual tasks better, quicker, and therefore cheaper. These trends are illustrated in Figures 10 and 11 over a 20 year period since the introduction of the Boeing 707. As with the JT3 engine, when the Boeing 707 was first introduced this aircraft represented a radical change in technology level. In the first year or two of ownership, maintenance costs were relatively low because of the airplane's newness. However, a peak cost level occurred in the third year of ownership (707-123 data), after which costs steadily declined until a mature level was finally reached about 12 years after introduction. These mature costs also occurred at a magnitude less than half that of the peak cost and again are lower, in terms of constant year dollars, than the cost encountered when the airplane was new. Derivative aircraft, such as the Boeing 707-323B benefited from this experience. This aircraft, introduced into American Airlines 8 years later, shows the same general trend of low initial cost to peak several years later and finally, a mature cost at about the same level as that of the original high time B707-123B fleet. Other data for the B727, B747, and DC10 indicate that these latter aircraft experience airframe maintenance trends similar to that of derivative B707 aircraft but without a peak. This is not surprising since airframe technology did not greatly change with the introduction of the wide-body aircraft, whereas their engines, each being an example of improving technology, followed a pattern similar to that of the original JT3 engine (Figure 3).

Designers of new technology aircraft (e.g., composite primary structure and lamina flow control), must guard against the possibility of high introductory and ongoing airplane maintenance costs by techniques such as "design for maintenance" or some other control measure which ensures low cost maintenance reliability of the new technology. Figures 3, 10, and 11 also illustrate why airlines become apprehensive when researchers talk of introducing radically new technology airplanes and/or engines.

Figure 12 compares the present cost model (See Data Points) predictions for airframe maintenance with the actual costs for various aircraft in 1976. Reasonable agreement was obtained across a broad grouping of transport. Similar correlation was obtained for the propulsion system costs. Maintenance cost results for the present airframe and propulsion system models are compared with the ATA Model (adjusted for inflation) in Figures 13 & 14. In the case of the airframe system model, the original 1967 form is, of course, inadequate and considerably overstates maintenance costs.

OTHER AIRPLANE RELATED OPERATING COSTS

In addition to airframe and propulsion system maintenance costs, other costs affecting airline operation were reviewed. One example is Flight Crew pay. Flight Crew pay increases with increasing flight length and maximum takeoff gross weight (Figure 15) because these two parameters are generally defined in U. S. union contracts as the prime determinants of a pilot's pay. Because of this weight - pay relationship, the highest Flight Crew pay in the American Airlines' system was obtained by pilot's flying high gross weight freighter or passenger aircraft, rather than those flying the lighter weight freighter and passenger aircraft. Technology which reduces maximum aircraft weight while accomplishing the same mission (example - composite materials) provides some hope of reducing both fuel burn and Flight Crew costs, provided that this basic rule of pay determination is not altered in future union contracts.

Improved flight control technology, cockpit automation, advanced displays, etc. and corresponding improvements in Air Traffic Control technology that accommodates the advances in airplane technology may, by a substantial reduction in cockpit workload, eventually eliminate the need for the third crew member, permitting a further reduction in Flight Crew costs.

Although Flight Attendant costs are currently considered part of an airline's indirect operating cost in the CAB system of accounts, Federal Regulations require flight attendants on most passenger carrying aircraft on the basis of seating capacity.

As a result of the liberalization of flight attendants employment requirements, the average tenure of flight attendants in the industry has progressively increased. This increase in seniority of service, plus lucrative union negotiated contract settlements makes this item of expense of more significance than in the past.

The basic premise on the need for flight attendants is passenger safety. Programs that are directed toward improving aircraft safety and facilitating the egress of passengers (including the handicapped) from an airplane in the event of an accident, could assist airlines and regulatory agencies in reducing the minimum required complement of attendants on each flight. In addition, improvements in passenger service items that are directed toward reducing the workload of flight attendants (microwave ovens, automated bar service, etc.) could also have a similar beneficial effect.

Figure 16 expresses the average flight attendant crew complement direct pay as a function of the number of aircraft seats and flight length. This display also takes into consideration the effect of variable "manning" techniques designed to recognize variations in load factors on specific flights, degree of passenger service provided, and the regulated minimum complement, regardless of passenger load.

The introduction of a new aircraft can cause a significant "spares" startup expense. In the example given in Figure 17 American Airlines' investment in airframe and engine spares as a ratio of its total investment in airframe and engines is initially very high because the airline has only a few copies of the model in its fleet and has overstocked many parts at advantageous prices as a precautionary measure. The relatively rapid fleet buildup which normally occurs after delivery of the initial aircraft dramatically reduces this cost ratio in the first two years of the fleet's life. A much smaller cost ratio reduction then occurs in latter years as the airline uses up its excess parts inventory and better manages the product and purchase of replacement parts, concentrating on those parts which have demonstrated a high likelihood of early failure. Introduction of a mature aircraft to an airline fleet usually results in a lower introductory cost than is shown here since the airline is able to benefit from the startup experience of other airlines.

To prorate certain fixed costs such as depreciation and spares, it is also necessary to estimate aircraft utilization. Therefore, variations in the use of individual airplanes were reviewed. This work indicated the main factors affecting aircraft utilization were individual airline route structure and the degree of passenger demand. Using this and other trip information, trips made per unit of time were analyzed. Figures 18 and 19 show how the number of trips vary as a function of stage length and flight length respectively. Data correlations were obtained from this information and were used in calculating costs which are dependent on aircraft utilization.

AIRCRAFT RELATED OPERATING COST MODELING

Table VIII and Figure 20 display the results obtained by exercising the model given in Table V for two hypothetical 170 passenger airplanes over a representative stage length of 1609KM (1000 statue miles).

In this instance, fuel expenditures play a major role in the cost per seat departure for the advanced technology airplane being $4.12 less than the current technology derivative airplane. This difference would continue to expand as fuel price increases occurred.

This is a significant factor (over 10% improvement) which would be almost impossible to offset even by major reductions in other cost factors (i.e. ownership, flight crew, maintenance cost, etc.) for the current technology airplane.

To add further impact to the developed numbers, the advanced technology airplane, on the basis of 1000 departures per airplane per year over a 1609 KM stage length, has the potential of reducing annual aircraft related operating expenditures by $700,400 per airplane.

Because the developed costs project such an air of realism, it is again essential to remind the reader that the methodology is for comparative purposes only and should not be considered as absolute.

CONCLUSION

A detailed study of airframe and propulsion system maintenance cost has been made which permits a better understanding of the factors that cause these costs. High airframe and engine maintenance cost areas were identified for various aircraft and engine types.

The data and techniques described here and in the NASA Reports should prove useful to airlines and manufacturers who are interested in analyzing and controlling their maintenance costs.

A new approach to airline operating cost modeling was developed and exercised. This approach may also be useful to those interested in estimating comparative airline operating costs of both existing and advanced technology aircraft.

The work described here could serve as a first effort towards determining many of the underlying factors which impact airline operating costs and, by analysis of its own historical data, each airline can determine for itself the relative importance of these cost factors and modify the basic models accordingly.

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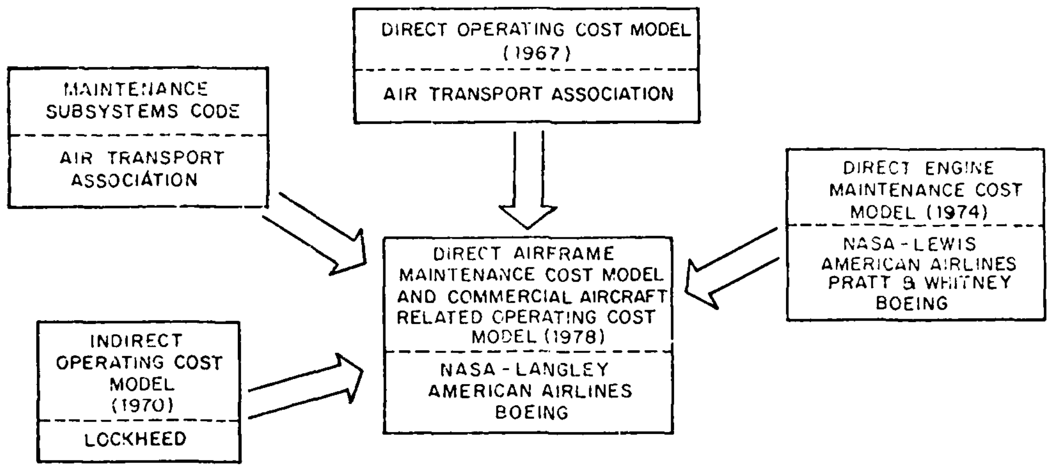

FIG. 1 COST MODEL EVOLUTION

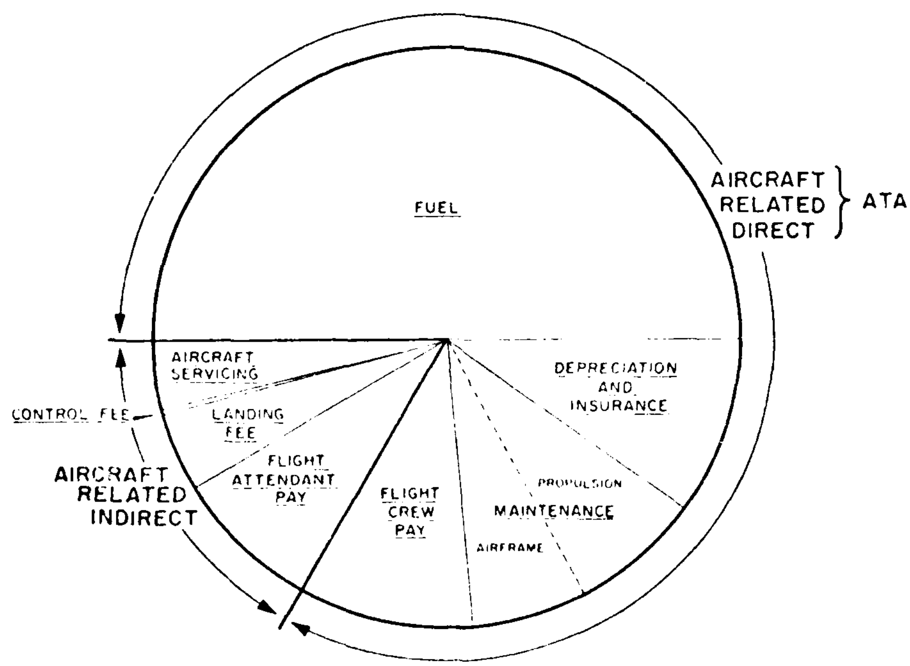

FIG 2 DISTRIBUTION OF DC-10 AIRPLANE RELATED DIRECT OPERATING COST

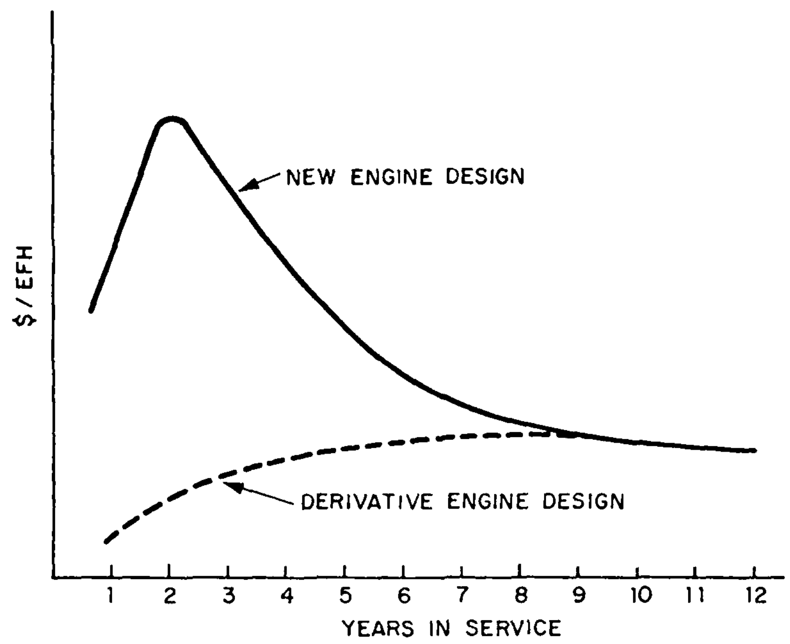

FIG. 3 TOTAL MAINTENANCE COST PER ENGINE FLIGHT HOUR VS. TIME

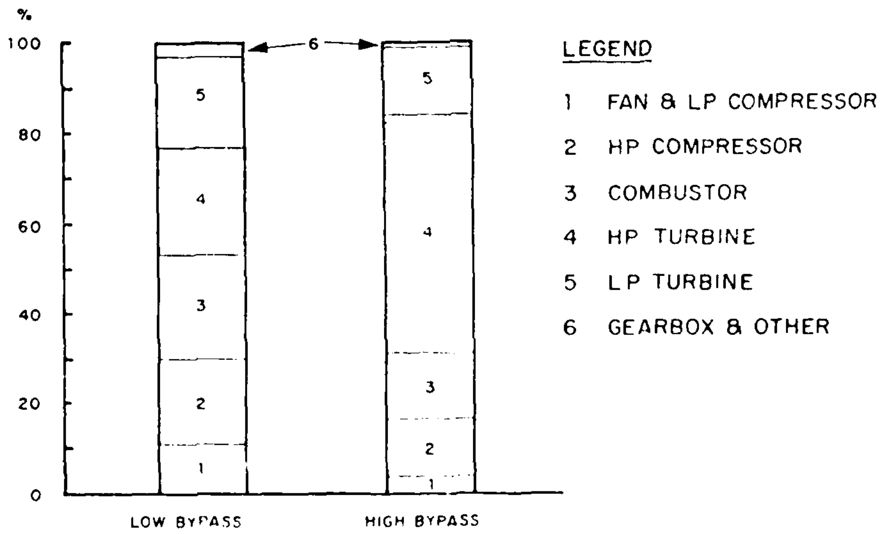

FIG. 4 RELATIVE CONTRIBUTION OF ENGINE MODULE SECTION TO TOTAL MAINTENANCE MATERIAL COSTS

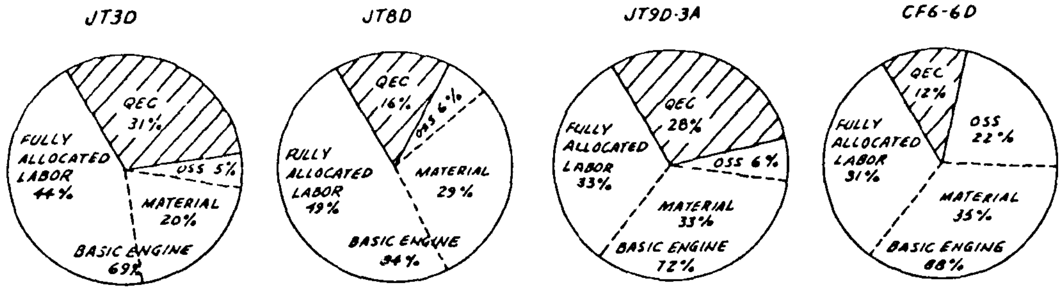

Figure 5 Powerplant Maintenance Cost Breakdown

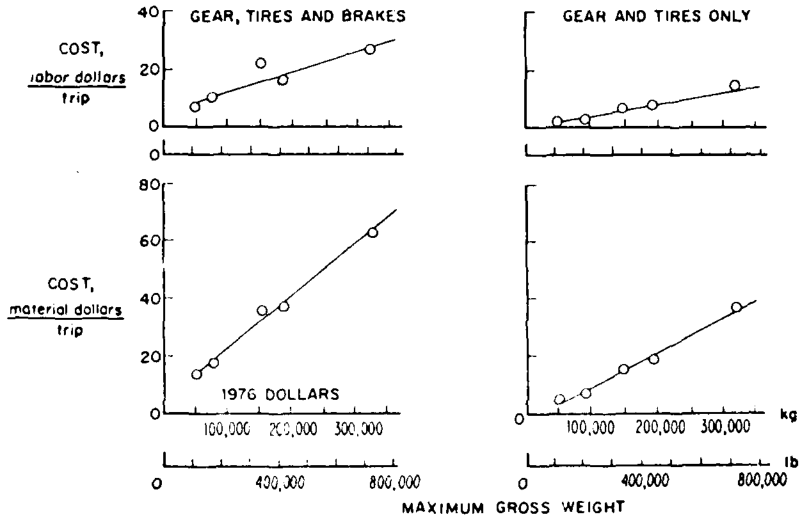

FIG. 6 LANDING GEAR OPERATING EXPENSE FOR U.S. DOMESTIC FLEET

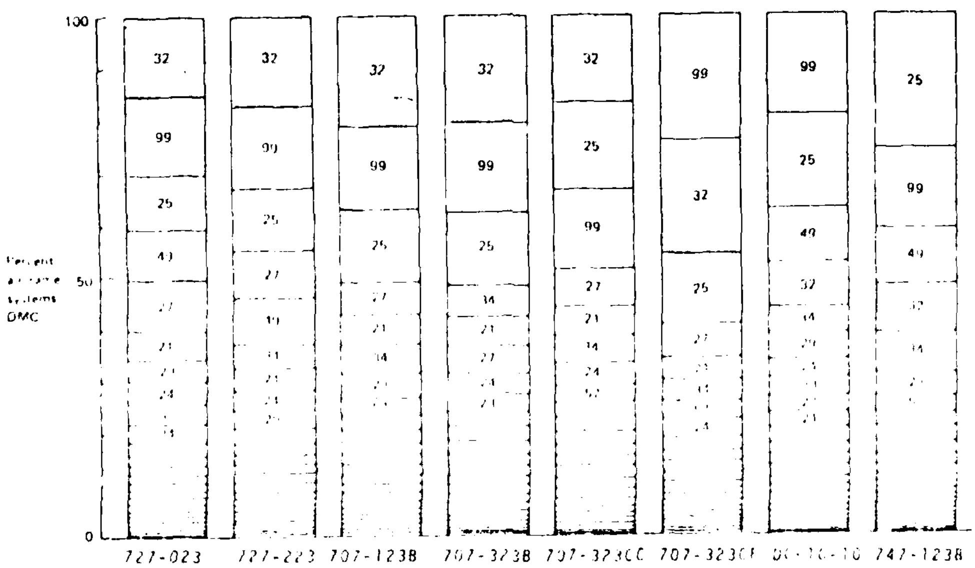

Figure 7 – Airframe Systems Maintenance Cost Distributions—American Airlines

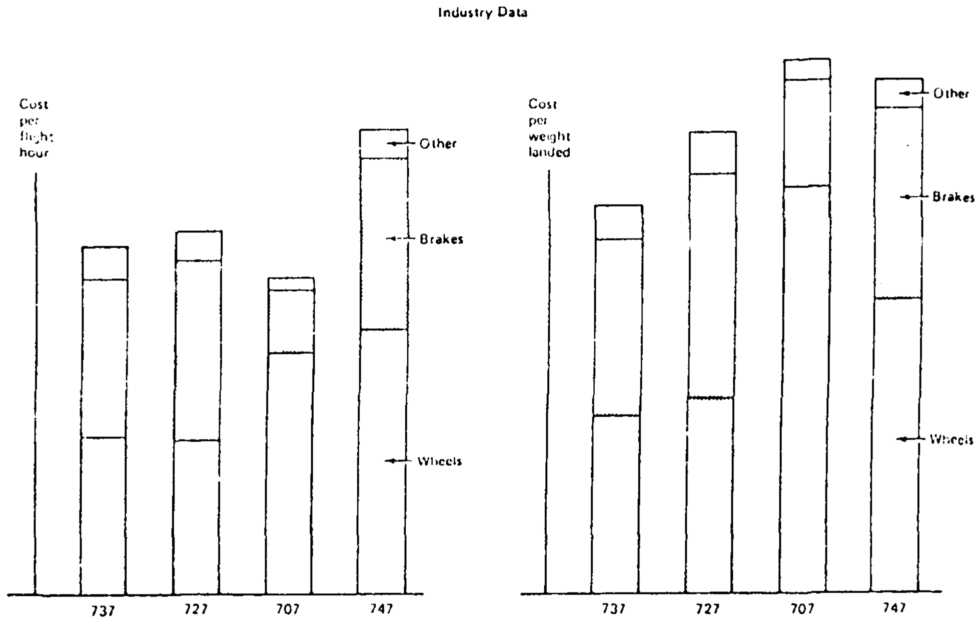

Figure 8—ATA System 32—Landing Gear Maintenance

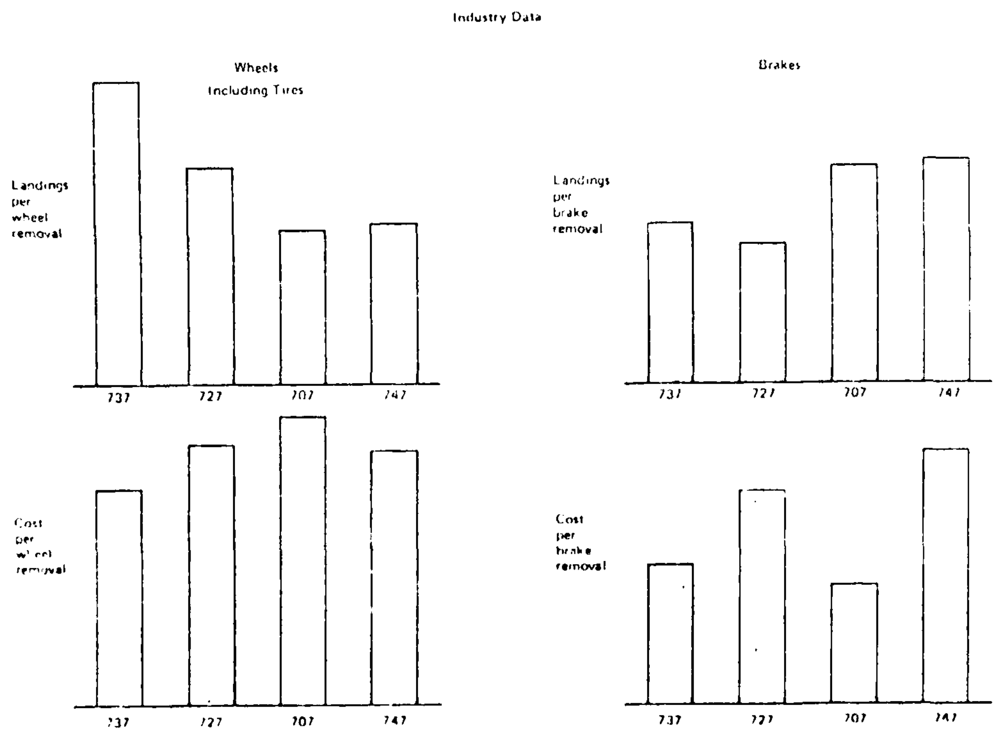

Figure 9 —Wheel and Brake Maintenance

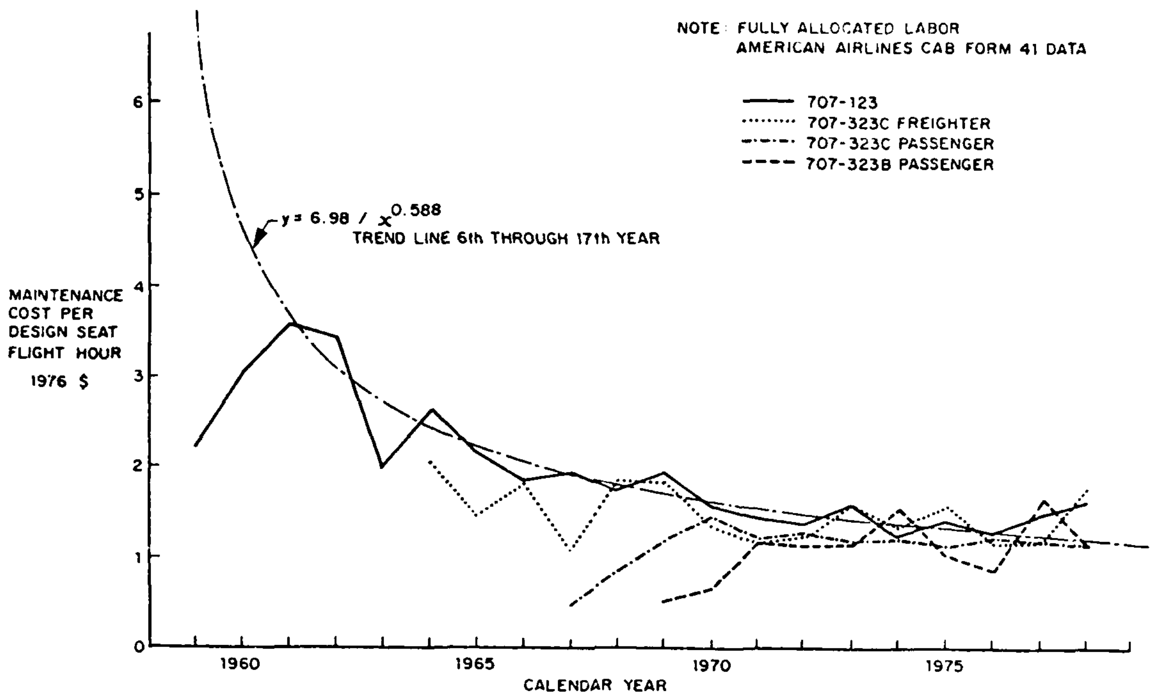

FIG. 10 AIRFRAME MAINTENANCE COST HISTORICAL TRENDS - MODEL 707 AIRCRAFT

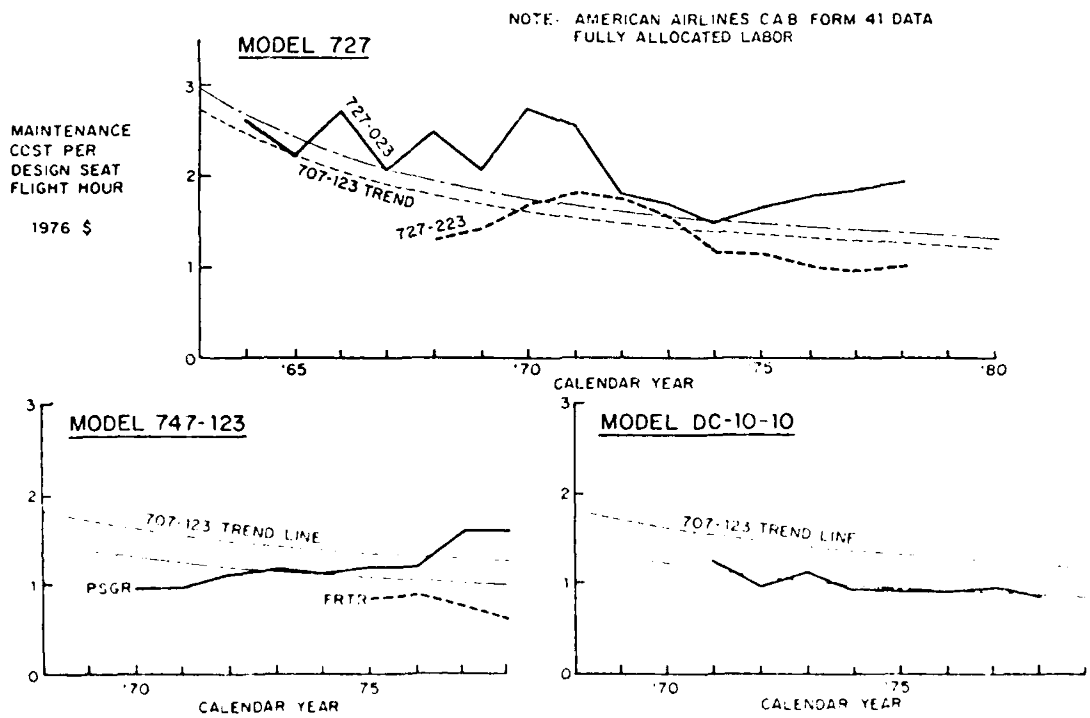

FIG. 11 AIRFRAME MAINTENANCE COST HISTORICAL TRENDS - 727, 747 & DC-10 AIRCRAFT

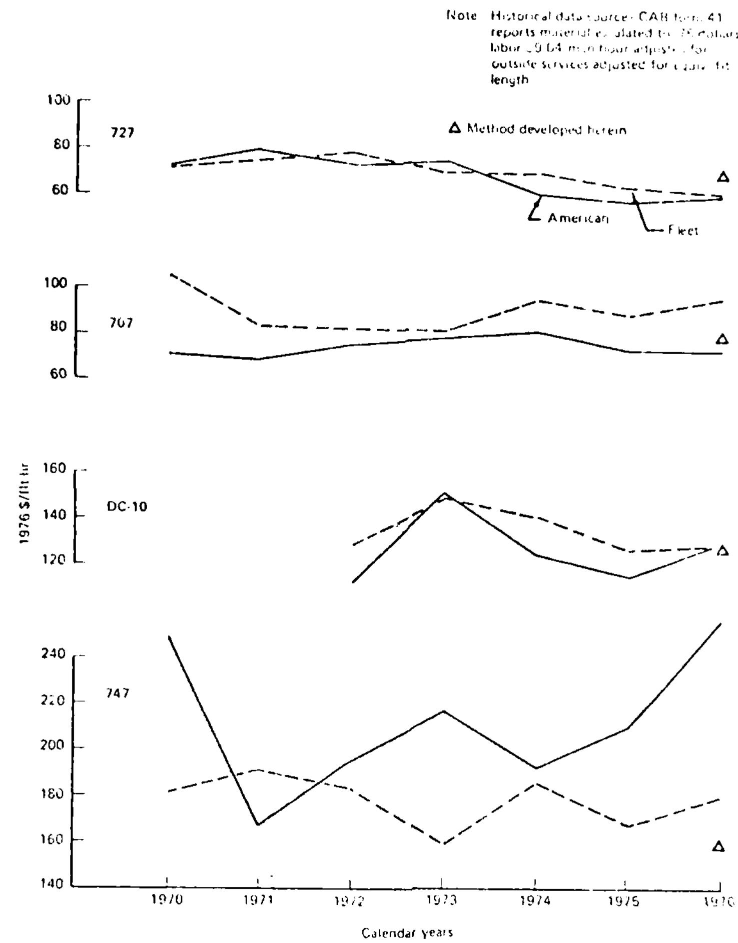

Figure 12 —Airframe Maintenance—1976 Dollars Per Flight Hour

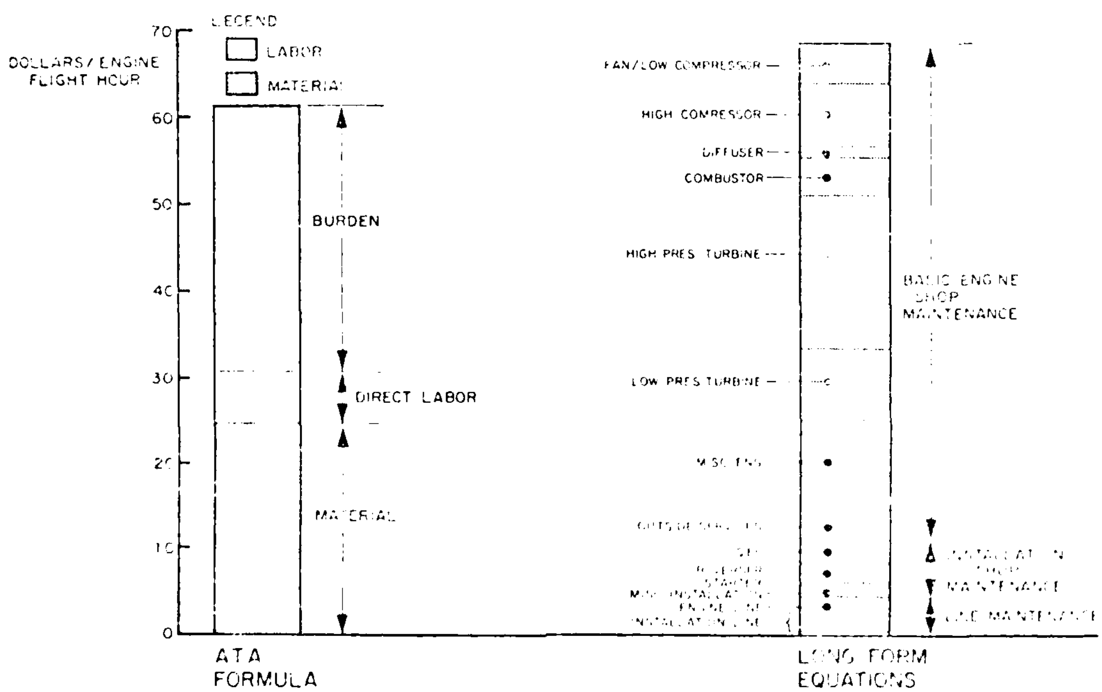

FIG. 13 ENGINE MAINTENANCE COST METHODS COMPARISON

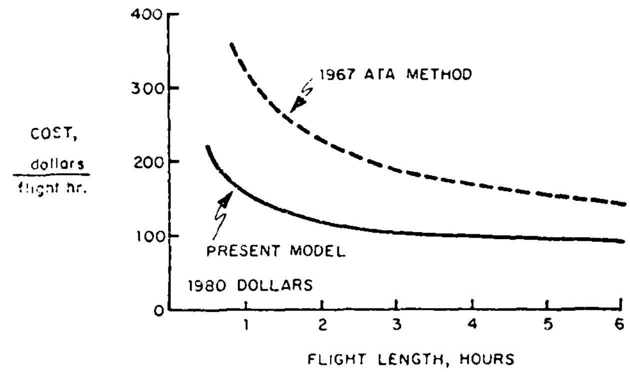

FIG. 14 AIRFRAME MAINTENANCE COST MODEL RESULTS FOR WIDE-BODY TYPE AIRCRAFT (ABOUT 150 PASSENGERS)

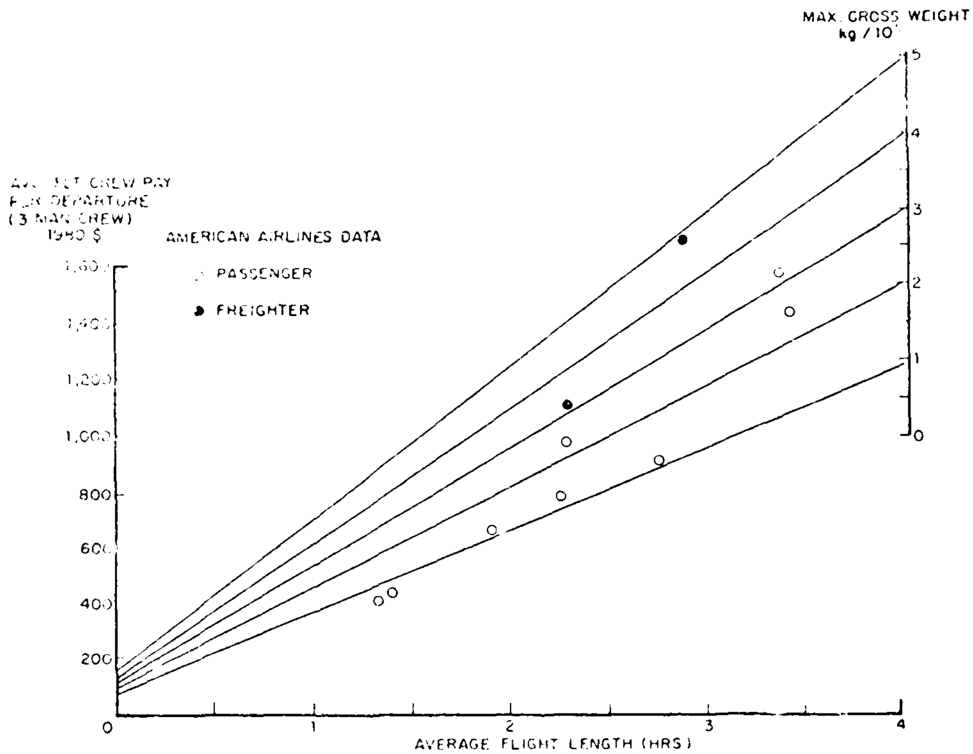

FIG. 15 DISTRIBUTION OF FLIGHT CREW PAY PER DEPARTURE AS A FUNCTION OF FLIGHT LENGTH AND GROSS WEIGHT

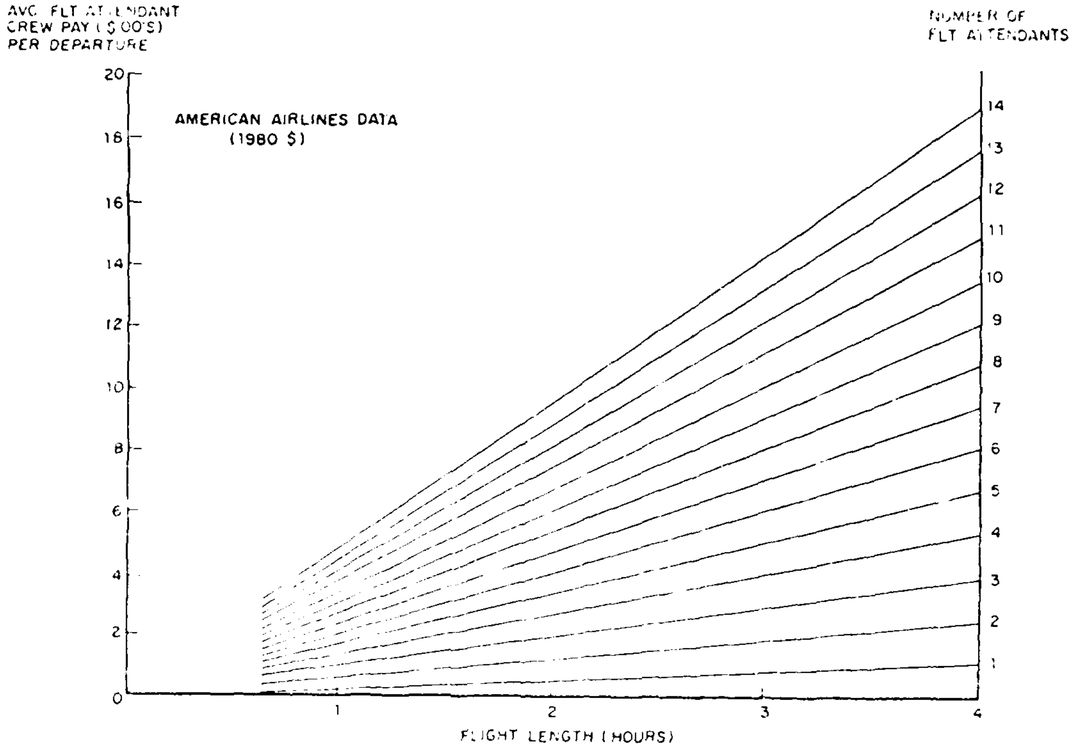

FIG. 16 DISTRIBUTION OF FLIGHT ATTENDENT CREW PAY PER DEPARTURE AS A FUNCTION OF FLIGHT LENGTH

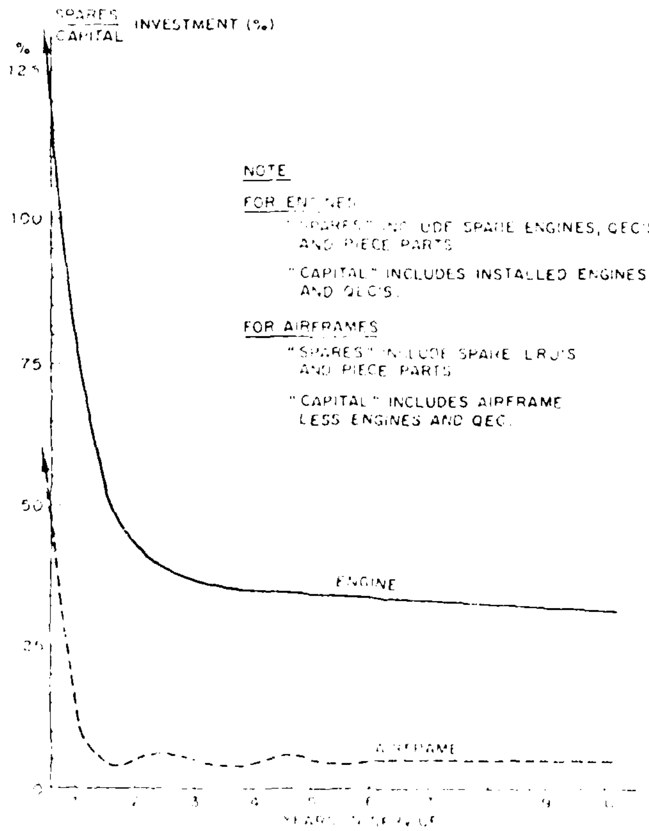

FIG. 17 SPARES INVESTMENT ($) VS CAPITAL INVESTMENT ($) VS YRS IN SERVICE

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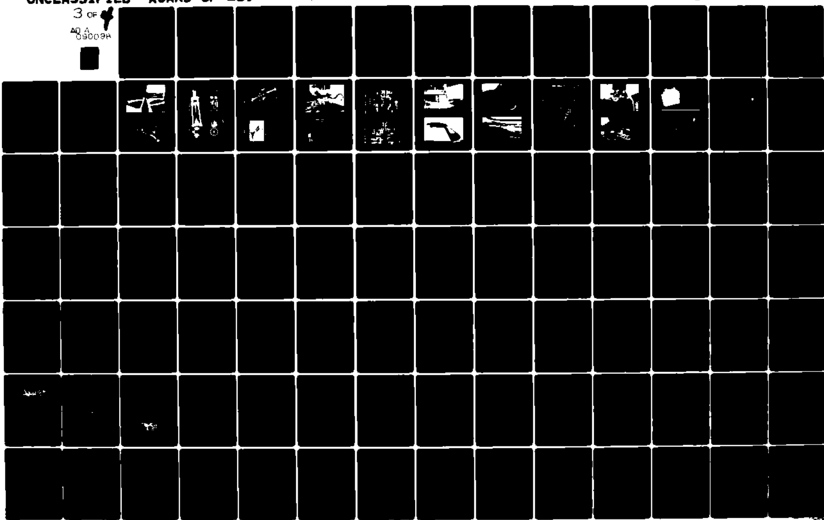

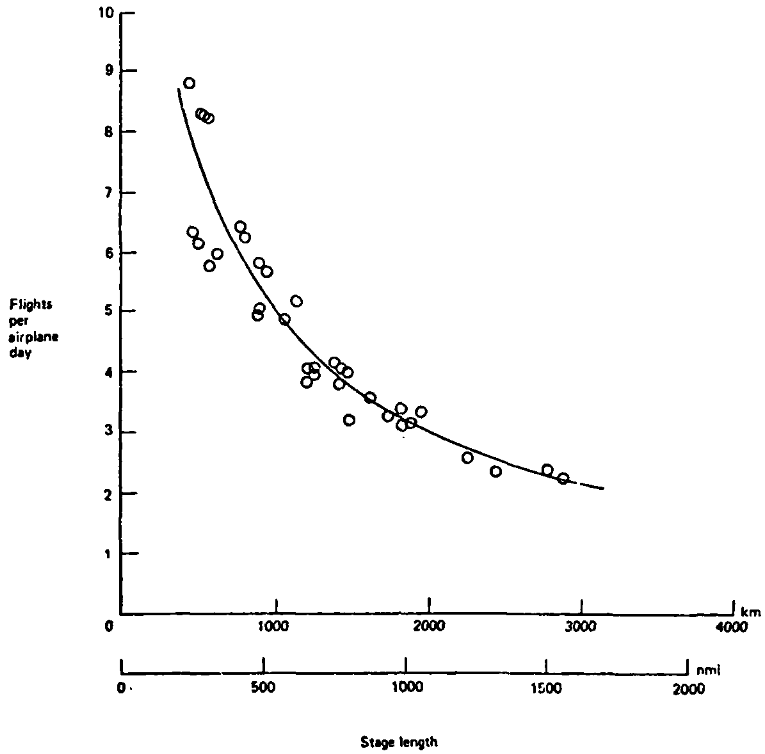

Figure 18–Fleet Average Trips Per Day

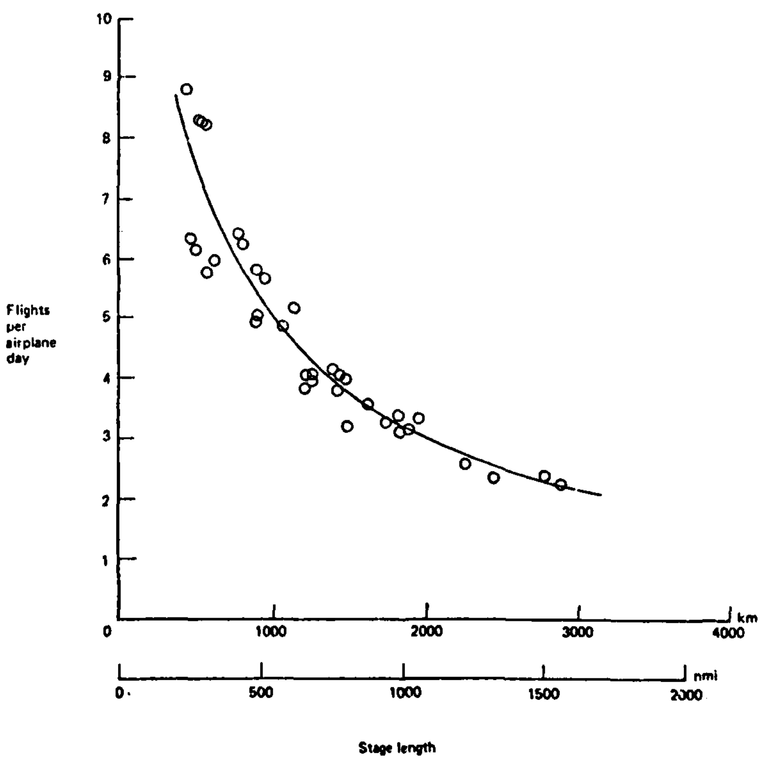

Figure 19–Fleet Average Trips Per Day

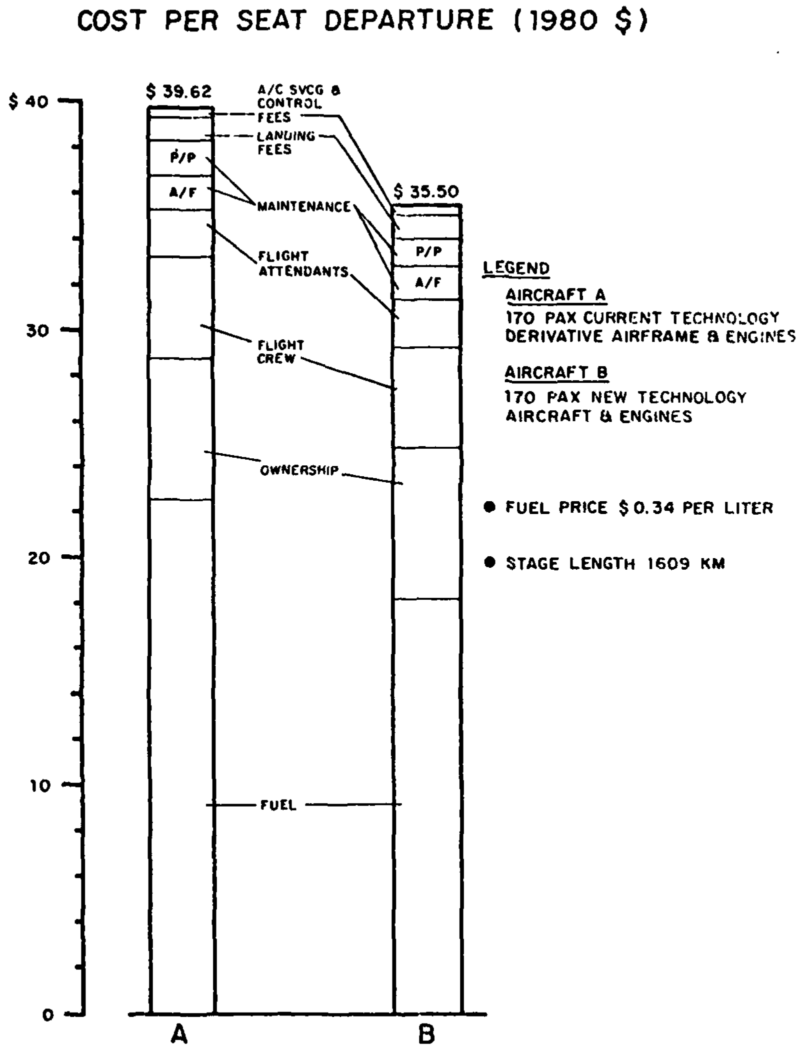

FIG. 20 AIRCRAFT RELATED OPERATING COST COMPARISON

1. Airframe (Excluding Engines)

A. Labor $= C_{am} = \dfrac{K_{FH_a}\ t_f + K_{FC_a}\ (R_L)\ (M^{1/2})}{V_b\ t_b}$

Where $K_{FC_a} = 0.05\ \dfrac{W_a}{1000} + 6 - \left(\dfrac{630}{\left(\dfrac{W_a}{1000} + 120\right)}\right)$ Labor man-hours per flight cycle

$K_{FH_a} = 0.59\ K_{FC_a}$ Labor man-hours per flight hour

B. Material $= C_{am} = \dfrac{C_{FH_a}\ t_f\ + C_{FH_a}}{V_b\ \ t_b}$

Where $C_{FH_a} = 3.05\ C_a\ /10^6$ material dollars per flight hour

$C_{FC_a} = 6.24\ C_a/10^6$ material dollars per flight cycle

2. Engine

A. Labor $= C_{am} = \dfrac{K_{FH_e}\ t_f + K_{FH_e}\ (R_L)}{V_b\ \ t_b}$

Where $K_{FH_e} = (0.6 + 0.027\ T/10^3)\ N_e$ Labor man-hours per flight hour

$K_{FH_e} = (0.3 + 0.03\ T/10^3)\ N_e$ Labor man-hours per flight cycle

B. Material $= C_{am} = \dfrac{C_{FH_e}\ t_f + C_{FC_e}}{V_b\ \ t_b}$

Where $C_{FH_e} = 2.5\ N_e\ \ (C_e\ /10^5)$ Mtrl. $ per flight hour

$C_{FC_e} = (2.0\ N_e\ (C_e/10^5)$ Mtrl. $ per flight cycle

Where:

C Cost, $)
K Labor, Man-hours) Subscripts
N Number)
  a Airframe
  am Per airplane statute mile
  e Engine
  FH Per flight hour
  FC Per flight cycle
V Speed, mph) Subscripts
t time, hours)
  b block
  f flight
M Cruise Mach Number (Assume 1 for Subsonic airplanes)
R_L Labor rate, $/hr ($4.00)
T Maximum certified takeoff thrust
W_a Basic empty weight of airplane less engines, lbs.

TABLE I - 1967 ATA Maintenance Cost Methodology

Mean time between repair – hours (MTBR)
= 0.83 x critical module MTBR of table

Basic engine maintenance shop costs

Labor manhours/flight

$$= \left[\sum_{o}^{6 \text{ modules}} (\text{manhours/repair})/\text{MTBR} + .19 \right] \times 1.064 \times FL^{0.72}$$

Maintenance materials/flight

$$= \left[\sum_{o}^{6 \text{ modules}} (\text{materials/repair})/\text{MTBR} \right] \times 1.18 \times FL^{0.72}$$

Propulsion systems outside service costs
= 0.065 x basic engine shop materials
+ 0.195 x basic engine direct labor $

Other propulsion systems maintenance costs
Labor manhours/flight

$$= 0.0440 + 0.143 \times FL + \left\{ FL^{0.72} (280 + 0.075\, W_e) / \text{MTBR} \right\}$$

if not core reverser subtract (0.0186 + 0.0612 FL)

Materials/flight

$$= 0.326 + 0.879 \times FL + (0.00383 \times ES \times FL^{0.72} / \text{MTBR})$$

if no core reverser subtract (0.131 + 0.231 FL)

To estimate maturity effect use the following factor on mature levels (as calculated above) for first five year average

MTBR	$(2.2)^{-1}$
Manhours/repair	0.7
Materials $/repair	0.7

Note: These equations differ from those published previously in NASA Report NASCR 134645 (4) in that they have been updated to reflect

1. 1980 $
2. Metric units
3. Outside services calculated using direct labor in lieu of fully allocated labor
4. Cost per flight departure in lieu of cost per flight hour.

Table II -Propulsion Systems Maintenance Costs
(Long Form Method)

(per engine 1980$)

Module	Mean time between repair – hours	Manhours per repair	Materials cost per repair – $
Fan low compressor	$4410/Y_{LPC}^{0.874}$	$.95 \times Z_{LPC} + 23$	0.125 x module price
High compressor	$4410/Y_{HPC}^{0.874}$	$.95 \times Z_{HPC} + 33$	0.114 x module price
Diffuser	5000	175	0.164 x module price
Combustor	$-2.25 \times Y_{CBS} + 4500$	250	0.124 x module price
High turbine	$-711 \times Y_{HPT} + 5650$	$1.78 \times Z_{HPT}^{0.611}$	0.238 x module price
Low turbine	$-711 \times Y_{LPT} + 5650$	$1.78 \times Z_{LPT}^{0.611}$	0.089 x module price

where

$$Y_{LPC} = T_3 \times \left(P_3/P_2\right)^{1/N(LPC)} \times U_{LPC} \times 10^{-6}$$

$$Z_{LPC} = \left[\left(U^2_{FAN} \times D_{FAN} \times N_{FAN}\right) + \left(U^2_{LPC} \times D_{LPC} \times N_{LPC}\right)\right] \times 10^{-8}$$

$$Y_{HPC} = T_4 \times \left(P_4/P_3\right)^{1/N(HPC)} \times U_{HPC} \times 10^{-6}$$

$$Z_{HPC} = U^2_{HPC} \times D_{HPC} \times N_{HPC} \times 10^{-8}$$

$$Y_{CBS} = T_5 - T_4$$

$$Y_{HPT} = T_5^{0.5} \times P_5/P_6 \times U_{HPT} \times N_{HPT} \times 10^{-5}$$

$$Z_{HPT} = T_5^{0.5} \times D_{HPT} \times N_{HPT}$$

$$Y_{LPT} = T_6^{0.5} \times P_6/P_7 \times U_{LPT} \times N_{LPT} \times 10^{-5}$$

$$Z_{LPT} = T_6^{0.5} \times D_{LPT} \times N_{LPT}$$

Table IIA - Basic Engine Module Maintenance Cost Forecasting-
Long Form Method

	ATA System	Labor	Material
99	Inspection and miscellaneous	10.69 + 0.526 x AFW/10^3	1.65 + 0.084 x AFW/10^3
21	Air conditioning	2.846 + 0.02139 x AC	3.16 + 0.015 x AC
22	Autopilot	3.124 x (N)CHANN	0.858 + 0.541 x (N)CHANN
23	Communications	0.02474 x Seats (w/o MUX) 0.0385 x Seats (w/MUX)	0.00943 x Seats (w/o MUX) 0.0161 x Seats (w/MUX)
24	Electrical	1.865 + 0.00553 x (N)GEN x KVA	1.932 + 0.00785 x (N)GEN x KVA
25	Equipment and furnishings	12.72 + 0.0741 x Seats x CF	3.24 + 0.0491x Seats x CF
26	Fire protection	0.1014 x ((N)ENG + (N)APU)* 0.297 + 14.461 x ((N)ENG+(N)APU)**	0.112 + 0.0751 x ((N)ENG + (N)APU)* 0.497 x ((N)ENG + (N)APU)**
27	Flight controls	9.55 + 0.00489 x MGW/10^3	5.273 + 0.00891 x MGW/10^3
28	Fuel	1.555 + 0.0366 x Fuel/10^3	0.809 + 0.0167 x Fuel/10^3
29	Hydraulic power	3.22 + 0.0048 x HYD	2.11 + 0.0109 x HYD
30	Ice and rain	0.7104 + 0.0018 x MGW/10^3	0.114 + 0.005 x MGW/10^3
31	Instruments	0.711 + 0.013 x AFW/10^3	0.32 + 0.0042 x AFW/10^3
32	Landing gear	6.77 + 0.0991 x MGW/10^3	6.749 + 0.246 x MGW/10^3
33	Lighting	2.11 + 0.01 x Seats x CF	0.064 + 0.0118 x Seats x CF
34	Navigation	4.104 + 2.93 x (N)INS + 5.0 x CF	0.117 + 1.63 x (N)INS + 5.0 x CF
35	Oxygen	0.719 + 0.00370 x Seats	0.00623 x Seats (Conventional) 0.1023 x Seats (OXY GEN)
36	Pneumatics	0.253 + 0.0042 + 0.0042 x AC x Thrust/10^4	0.0026 x AC x Thrust/10^4
38	Water/waste	0.473 + 0.0032 x Seats x CF	0.0066 x Seats x CF
49	Airborne auxiliary power	1.003 + 0.0004 x (APU-SHP x APU-FR)$^{1/2}$ (x 1.8 for double spool, variable vanes)	1.994 + 0.001 x (APU-SHPxAPU-FR)$^{1/2}$ (Labor and material cost per APU operating hour)
50	Structures	4.188 + 0.0138 x AFW/10^3	
52	Doors	1.60 + 0.008 x Seats	0.527 + 0.01068 x Seats
53	Fuselage	2.09 + 0.064 x AFW/10^3	0.79357
54	Nacelles/pylons	0.47 x Pod NAC	0.18924 Pod NAC
55	Stabilizers	1.164	0.5084
56	Windows	1.065 + 0.0006 x Seats	0.0386 x Seats (Flat Windshield) 0.0493 x Seats (Curved windshield)
57	Wings	4.1147	0.171 + 0.00688 x Wing Area

*Single circuit
**Dual circuit

TABLE III - AIRFRAME MAINTENANCE SYSTEM COST EQUATIONS (2.5 Flight Hours)

ABBREVIATIONS

AC	air conditioning total pack air flow, kg/min
AFW	airframe weight, (manufacturer's empty weight-includes engine's furnishings, etc. - excludes operator's items) kg
APU	airborne auxiliary power unit
CF	defined "complexity" factor = short range operations 0.6; medium range 1.0; long range 1.6
CHANN	channels
ENG	engines
Fuel	fuel capacity, kg
FR	air conditioning flow rate output, kg/min
GEN	electrical generators
HYD	flow of hydraulic pumps, l/min
INS	inertial navigation system
KVA	kilovolt amperes
MGW	maximum gross weight (max. taxi weight), kg
MUX	multiplex unit
N	number of
NAC	nacelle
OXY GEN	oxygen generator
SHP	shaft horsepower, watts
Thrust	thrust, N
Wing area	wing area, m^2

CBS	Combustor module
CET	Combustor exit temperature, degrees K
D	Diameter, m
DIF	Diffuser module
ES	Engine price, 1980 $
FAN/LPC or LPC	Fan and low pressure compressor module
HPC	High pressure compressor module
HPT	High pressure turbine module
LPT	Low pressure turbine module
MTBR	Mean time between repair or removal, hours.
P	Pressure, absolute, newtons per sq. m.
T	Temperature, degrees K
U	Tip speed, m/sec

TABLE IV - ABBREVIATIONS

The total airplane related operating costs may be stated as follows:
Operating costs (1980 $/trip)=

Depreciation	$= \dfrac{\text{Purchase price* - residual}}{\text{Depreciation period}} \times \dfrac{1}{N}$
+ Insurance	$= \dfrac{\text{1\% of purchase price+}}{N}$
+ Control fee	= $9.77 without data link or = $5.58 with data link
+ Landing fee	= $2.20/1000 kg of landing weight
+ Aircraft servicing Narrow body	= 0.02 x seats x $12.98/man-hour (labor) +0.0002 x seats (material)
or Wide body	= 0.033 x seats x $12.98/man-hour (labor) +0.003 x seats (material)
+ Flight attendant pay	$= (0.964 \times FL + 0.00244 \times (FL)^2) \times \text{seats}$
+ Flight crew pay**	$= 243 \times FL + 60.73 + (0.631 \times FL + 0.15773) \times \dfrac{MGW}{1000}\text{kg}$
+ Fuel expense	$= \dfrac{\text{Liters}}{\text{Trip}} \times \dfrac{\text{Dollars}}{\text{Liter}}$
+ Maintenance cost	See section Tables II & III
where FL	= Flight length, hours

Utilization=N=No. of departures per year = $\dfrac{3205}{FL + 0.327}$

Note: To determine airplane related costs in other than 1980$, apply escalation factors determined by experience or from data published in the Metals and Metal Products section of the Wholesale Prices Index-Code 10 and the Gross Earnings of Production Workers in the Aircraft Industry-SIC372-Bureau of Labor.

*Including airframe and engine spares
**The expression given is for a 3 man crew-for a two man crew, use 75% of this value.
+Does not include airframe and engine spares.

TABLE V - AIRCRAFT RELATED OPERATING COST METHODOLOGY

The required dimensional characteristics are as follows:

CET — Combustor exit temperature T_5, degree K

Dxxx — Diameter, inches subscripts or 0.3937 x diameter cm subscripts

- LPC - first stage blade tip
- HPC - first stage blade tip
- HPT - first stage blade tip
- LPT - first stage blade tip
- FAN - fan blade tip

E$ — engine price in 1980$

MTBR — mean time between repair or removal

Nxxx — number of stages in module xxx except subscript LPC - number of stages in fan plus number of stages in low pressure compressor

Px — pressure, newtons per sq. m absolute, sea level takeoff, hot day

Tx — temperature, degree K, sea level takeoff, hot day subscripts

- 2 - LPC inlet
- 3 - LPC exit
- 4 - HPC exit
- 5 - combustor exit
- 6 - HPT exit
- 7 - LPT exit

Uxxx — tip speeds, ft/sec, 0.3045 m/sec, sea level takeoff, hot day (use first stage blade tip except for U(LPC) - FAN/LPC module use weighted average blade tip speed).

TABLE VI- ENGINE MAINTENANCE COST DEPENDANT VARIABLES

Airframe Weight
Labor Rate
Material Expense Factor
Max. Taxi Weight
Wing Area
Fuel Capacity
Windshield Type
Engines - Number/Thrust Rating
Nacelles - Number
Fire Extinguisher System - Single/Dual
Electrical Generators - Number/Capacity
Hydraulic Pump Flow
Seats
Airconditioning Flow Rate
Oxygen System - Gaseous/Solid State
Multiplex Installation
Autopilot Channels
Navigation System
Auxiliary Power Unit - Output Specs
Service Complexity Factors

TABLE VII- AIRFRAME MAINTENANCE COST DEPENDANT VARIABLES

CONDITIONS

STAGE LENGTH	1609 KM
FUEL PRICE	$0.34 PER LITER
FLIGHT LENGTH	2.21 FLIGHT HRS. 2.45 BLOCK HRS.

COST PER SEAT DEPARTURE 1980 ($)

ITEM

	AIRCRAFT A	AIRCRAFT B
OWNERSHIP (INCLUDES DEPRECIATION & INSURANCE)	6.27	6.70
TRIP FUEL	22.48	18.10
FLIGHT CREW (3)	4.41	4.36
FLIGHT ATTENDANTS (5)	2.14	2.14
AIRFRAME MTC.	1.49	1.48
PROPULSION MTC.	1.50	1.30
LANDING FEES	1.04	0.96
AIRCRAFT SERVICING	0.26	0.43
CONTROL FEES	0.03	0.03
TOTAL	39.62	35.50

TABLE VIII
AIRCRAFT RELATED OPERATING COST COMPARISON BETWEEN
TWO 170 PASSENGER AIRPLANES

Le "DESIGN TO COST" APPLIQUE à l'HELICOPTERE AS 350

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Sommaire

La nécessité d'une recherche de réduction des coûts s'est imposée à l'Aérospatiale pour ses hélicoptères bas de gamme afin de rester compétitif sur le marché international.

Cet effort de réduction des coûts s'est concrétisé, au terme de deux années de travail d'un petit groupe Etudes-Fabrication très expérimenté, par un avant-projet d'une nouvelle machine, l'AS 350, résolument plus économique que l'Alouette II ou la Gazelle et dont le développement puis l'industrialisation ont ensuite été lancés dans le même esprit de réduction des coûts.

La méthode utilisée est classique dans ses fondements :

- Analyse de la valeur des fonctions et des pièces assurant ces fonctions,
- Critique des solutions,
- Recherche de solutions nouvelles,
- Choix des compromis.

Elle n'a cependant pas été formalisée pour gagner du temps, balayer davantage de solutions possibles et parce que l'expérience des participants permettait d'éliminer rapidement, sans analyse détaillée, les solutions les plus chères et les moins performantes.

Tous les domaines, études, fabrication, contrôle, approvisionnements doivent concourir à la recherche du moindre coût.

Les bénéfices obtenus en procédant correctement, dès le stade conception, peuvent être très importants, aussi bien pour le coût d'acquisition que pour le coût d'utilisation. Cela intéresse non seulement les utilisateurs civils, ce qui est évident, mais aussi les utilisateurs militaires qui, pour le même budget, peuvent obtenir des matériels plus nombreux et plus efficaces.

L'hélicoptère AS 350 Astar ou Ecureuil est la première machine étudiée par la Division Hélicoptère de l'Aérospatiale avec un objectif de prix comme objectif prioritaire.

Cette préoccupation des coûts n'est cependant pas nouvelle et le graphique ci-contre montre que des progrès étaient régulièrement enregistrés en cette matière. Mais un effort spécial a été réalisé pour l'AS 350 pour réduire les coûts de production.

Pourquoi cet effort particulier, précisément pour l'AS 350 ?

Il est apparu, en 1971, qu'il était impératif d'améliorer la compétitivité de nos hélicoptères bas de gamme sur le marché international à cause des changements de parité franc-dollar. Une étude de réduction des coûts de production de l'Alouette II a donc été entreprise et les résultats ont été assez décevants. Les réductions de coût, possibles sans remise en cause importante des définitions et des outillages de production, ne dépassaient guère 5%. Cet exercice nous a permis cependant d'entrevoir la possibilité de réductions importantes des coûts de production par une reprise fondamentale de l'étude et la réalisation d'un appareil entièrement nouveau, utilisant toutes les possibilités offertes par les technologies nouvelles, et dont l'étude serait menée avec le prix comme objectif prioritaire.

Pendant une période de deux ans, une équipe Etudes-Fabrication très réduite, de 4 à 5 personnes, s'est attachée à bâtir un avant-projet pour lequel l'architecture de la machine a été définie, en même temps qu'étaient précisées ses caractéristiques générales de taille, de masse et de performances.

La définition des grands ensembles constitutifs était choisie et le dessin poussé assez loin pour que l'on puisse évaluer de façon suffisamment précise les masses et les prix. Les solutions choisies ont fait appel à de nouvelles technologies développées par ailleurs, mais aussi, très souvent, imaginées pour la circonstance.

Il est évident qu'un tel travail n'a pu être réalisé que par une équipe très expérimentée, très proche de la Direction des Etudes, fortement soutenue par elle et par la Direction de la Production.

Au terme de cette période d'avant-projet, on a pu démontrer qu'il était possible de réduire le nombre d'heures de fabrication dans un rapport de 1 à 3 par rapport à celui de l'Alouette II, et le lancement de l'opération "développement" a été décidé en avril 1973.

Ce travail de développement a été confié à une unité opérationnelle que nous appelons un "îlot" regroupant le personnel d'études, de fabrication et de mise au point sous l'autorité d'un responsable issu du Bureau d'Etudes.

La liasse des dessins de détail a été réalisée et n'a été libérée pour fabrication qu'après vérification des prix et des masses, en comparaison avec les prix et masses "objectifs" résultant de l'étude d'avant-projet.

La mise au point en laboratoire et en vol a naturellement donné lieu à des modifications dont la définition a été réalisée dans le même esprit de sauvegarde des prix et des masses "objectifs".

Le personnel détaché dans cet îlot développement ne perd pas pour autant le contact avec son service d'origine, dont il fait toujours partie. Ceci est important pour ne pas isoler ce personnel sur le plan technique comme sur le plan de la carrière personnelle.

Les définitions "développement" doivent naturellement être pensées "série", le travail d'analyse de la valeur effectué au stade avant-projet et développement n'aurait aucun sens si les définitions série étaient différentes.

Les outillages nécessaires pour réaliser les machines de développement peuvent être des outillages prototypes. Il convient cependant de s'assurer que l'outillage série ne peut pas être réalisé immédiatement en évaluant la probabilité de modification pouvant résulter de la mise au point. Dans certains cas, c est l'outillage prototype sommaire qui est intéressant parce que peu coûteux, rapide à réaliser et parce que les risques d'évolution sont élevés. Dans d'autres cas, on aura intérêt à réaliser immédiatement l'outillage de fabrication série parce que son prix n'est pas beaucoup plus élevé, parce qu'il permet une économie importante sur la réalisation des pièces prototypes et parce que les risques d'évolution sont faibles.

Pour la phase d'industrialisation, un homme de production devient leader. Le travail d'étude est d'ailleurs réduit à la validation des définitions prototypes, à l'intégration des modifications dans la liasse de dessins et au support technique de la production.

Le travail d'industrialisation consiste essentiellement à organiser la production, à définir et a réaliser les outillages de fabrication, à définir et à mettre au point les méthodes de fabrication.

Toutes les phases, avant-projet, développement et industrialisation sont importantes pour la recherche du coût minimal, mais la plus importante, celle qui conditionne les autres, c'est la phase d'avant-projet.

Il faut, le plus tôt possible, dès la phase de conception initiale, intervenir dans la définition du produit avec des préoccupations de prix. L'analyse de la valeur sur un produit déjà défini, à fortiori sur un produit déjà fabriqué, conduit à des résultats limités, souvent médiocres, parce qu'il est impossible, si l'on intervient tardivement, de remettre en cause fondamentalement la définition.

Nous avons vu dans quel cadre, dans quelle organisation s'est exercée la recherche du moindre coût pour l'AS 350. Voyons maintenant quelle a été la méthode de travail utilisée.

Quelle que soit cette méthode, ce sont toujours les mêmes principes qui sont à la base de la recherche du moindre coût :

- Analyse des fonctions et de leur coût qui conduit à en faire la critique, à les remettre en cause éventuellement, à porter un jugement sur leur nécessité ou leur formulation, compte tenu de la finalité globale du produit.

- Analyse des pièces constitutives et de leur coût qui permet une prise de conscience des éléments essentiels qui déterminent le coût et motive ainsi la créativité.

- Recherche de solutions nouvelles qu'il faut évaluer du point de vue prix mais aussi du point de vue masse, fiabilité, facilité de mise en oeuvre et d'entretien, risques techniques éventuels, etc. ...

- Choix du meilleur compromis. Le jugement est à porter en fonction des objectifs principaux cités plus haut et il faut définir des critères d'équivalence.

Par exemple, on ne peut accepter une réduction de coût qui conduit à un accroissement de masse trop important, préjudiciable à l'efficacité de l'appareil. A la limite, un hélicoptère d'un prix voisin de 0 mais dont la charge payante est nulle, est infiniment trop cher. Le critère d'équivalence masse - prix est très variable avec le type de machine et les missions qu'il doit remplir.

Au moment de l'étude de l'Ecureuil, nous l'avions fixé à 500 F par kg mais il est considérablement plus élevé pour une machine comme le Super-Puma.

Une équivalence du même genre peut être établie entre la réduction du coût de production et l'accroissement du coût d'utilisation. Bien que cela soit plus difficile et plus dépendant du coefficient d'importance que l'on accorde à tel ou tel aspect du problème, il est possible de définir là aussi un critere coût de fabrication - coût d'utilisation.

Il est rare d'ailleurs qu'un effort supplémentaire ne permette pas de trouver une solution satisfaisante à plusieurs sinon à tous les points de vue. Dans l'Ecureuil, c'est seulement dans deux cas, la verrière et la boîte de transmission, que les solutions plus économiques choisies ont conduit à un accroissement de la masse (modeste d'ailleurs) par rapport aux solutions antérieures utilisées sur Alouette II et sur Gazelle.

On peut naturellement formaliser ce travail d'analyse de la valeur en dressant des tableaux (comme on l'enseigne généralement) où on fait figurer horizontalement toutes les fonctions assurées par un ensemble et verticalement les pièces constitutives de cet ensemble en indiquant leur coût.

On peut ainsi déterminer le coût des diverses fonctions pour en faire la critique sous l'angle "coût-efficacité". De même, il est possible de déterminer le nombre de fonctions remplies par chaque pièce et de confronter le coût de ces pièces au nombre de fonctions assurées.

La recherche de solutions nouvelles donne lieu à l'établissement de nouveaux tableaux, autant que de solutions nouvelles.... On imagine aisément l'importance du travail que cela peut représenter pour des machines complexes, où, pour chaque ensemble constitutif (et ils sont nombreux) de très nombreuses solutions sont possibles.

Pour l'Ecureuil, le travail n'a pas été formalisé de cette manière. La constitution d'une équipe très expérimentée a permis de réaliser ce travail d'analyse des fonctions et de comparaison des solutions, sans faire de tableaux, sans même dessiner complètement les diverses solutions possibles et sans les chiffrer.

Avec l'expérience, il est souvent possible, d'un seul coup d'oeil, de juger si telle solution remplit correctement les fonctions requises et si elle est coûteuse ou non. Le travail peut alors se concentrer sur la recherche de solutions nouvelles plutôt que sur l'établissement de tableaux ou de calculs de prix fastidieux. C'est beaucoup plus rapide et beaucoup plus efficace. On prend le risque sans doute de passer à côté d'un fait qui peut avoir son importance et que le travail systématique d'analyse met en évidence à coup sûr. Mais cela est largement compensé par le nombre de solutions qu'on peut rapidement passer en revue et par l'exploitation plus poussée de la compétence des participants.

On ne saurait trop insister d'ailleurs sur la qualité nécessaire des participants. Les résultats à attendre d'un travail de ce genre en dépendent essentiellement, car il n'en sortira en définitive que ce que les hommes qui y participent sont capables d'apporter eux-mêmes. Les solutions choisies sont naturellement évaluées soigneusement et cette évaluation constitue l'objectif à respecter par la suite.

Le prix, comme la masse, est décomposé entre les différents ensembles et les dessins ne sont validés pour fabrication que si les devis sont respectés. En cas contraire, l'étude devra être reprise, à moins que des compensations soient trouvées ailleurs ....

De mauvaises surprises peuvent survenir en cours de développement qui remettent en cause partiellement les définitions choisies. Là encore l'étude sera reprise et le processus d'analyse de la valeur engagé à nouveau.

La recherche de réductions des coûts, pour être efficace, doit s'exercer dans tous les domaines et porter sur toutes les activités qui concourent à la réalisation du produit.

L'étude, bien entendu, qui en établit la définition, mais aussi le Service Approvisionnements qui doit, avec le Bureau d'Etudes, rechercher des matériaux ou des équipements plus économiques dont les caractéristiques seront juste adaptées, sans plus, aux spécifications nécessaires.

Les méthodes de fabrication qui doivent également être conçues dans un esprit d'économie et imaginées en même temps que le produit en cours d'étude. Bien souvent d'ailleurs, la définition dépendra des méthodes et des moyens de fabrication, ce qui met l'accent une fois de plus sur la nécessité impérative de la participation à l'étude des ingénieurs de fabrication.

Les méthodes de contrôle qui, elles aussi, sont étroitement associées à la définition du produit. On peut éviter un travail de contrôle important en pensant, au moment de l'étude, à la façon dont il sera effectué.

L'organisation même de la production a une importance, non seulement pour réduire les coûts de production d'un produit déterminé, mais pour en modifier la définition au stade de l'étude afin de l'adapter à une organisation efficace du travail.

Quelques exemples tirés de l'expérience Ecureuil permettront d'illustrer ces différents aspects de la question :

Le travail d'étude constitue la première activité où la réduction de coût est recherchée, et le moyen essentiel utilisé pour cela est évidemment l'innovation.

Le moyeu Starflex de l'Ecureuil est particulièrement démonstratif à ce point de vue.

On sait que, sur un moyeu d'hélicoptère, il faut assurer les diverses fonctions suivantes :
- Possibilité de mouvement vertical de la pale : le battement
- Possibilité de mouvement de la pale dans le plan rotor : la traînée
- Possibilité de mouvement de la pale en incidence : le changement de pas.

En outre, il faut, pour éviter certaines instabilités, résonance sol ou résonance air, placer correctement le premier mode d'oscillation des pales en traînée, et l'amortir convenablement.

De plus, il faut aussi supporter les pales au repos, rotor stoppé.

- Dans un moyeu classique comme celui de l'Alouette, les différents mouvements de la pale sont possibles grâce aux articulations de battement, de traînée et de pas, montées sur roulements à aiguilles. Les câbles de tierçage interpales remontent la fréquence d'oscillation des pales en trainée et des amortisseurs hydrauliques apportent l'amortissement de traînée nécessaire. Enfin, une butée sur anneau réciproque maintient les pales au repos.

- Dans le moyeu Starflex, les articulations de battement, de trainée et d'incidence sont assurées par la butée sphérique en élastomère lamifié.

  Les bras de l étoile, équipés en bout d'une rotule auto-lubrifiante, retiennent les pales à l'arrêt. Flexibles en battement, ces bras suivent les mouvements verticaux des pales tandis que, rigides en traînée, ils maintiennent les pales dans le plan rotor par l'intermédiaire de deux couches d'élastomère visco-élastique qui permettent un positionnement correct du mode de traînée, tout en fournissant un certain amortissement.

Le tableau de comparaison des moyeux Alouette et AS 350 permet d'apprécier la simplification apportée par le concept Starflex qui, outre sa simplicité, a permis :
- une réduction de masse de l'ordre de 45%,
- une amélioration de la fiabilité par sa bonne résistance à la fatigue, son caractère fail-safe, son insensibilité à la corrosion, aux effets d'entaille et aux impacts éventuels,
- une amélioration de la maintenance par les facilités de surveillance visuelles offertes et par le remplacement facile sur le terrain de n'importe lequel de ses composants,
- une réduction du coût de production de l'ordre de 1 à 3 par rapport au moyeu Alouette. Cette réduction atteint même le rapport de 1 à 5 par la mécanisation de la découpe et de la mise en place des tissus dans le moule.

Un autre exemple où l'étude a permis une réduction substantielle du coût concerne la boîte de transmission principale.

Il s'agit ici du choix d'une chaîne cinématique différente comportant un nombre d'étages de réduction plus réduit, un couple conique et un réducteur épicycloïdal au lieu d'un couple

conique et deux réducteurs épicycloïdaux.

En outre, la prise de mouvement arrière pour l'entraînement du rotor de queue a été supprimée, grâce à l'architecture du moteur offrant une prise de mouvement vers l'avant et vers l'arrière.

Le tableau de comparaison montre que le nombre de pignons et de roulements a été divisé par 2 environ. Le prix a subi une réduction analogue. Cependant, il a fallu consentir à un accroissement de masse de l'ordre de 12%, accepté volontiers compte tenu du gain important obtenu sur le coût de production, sur le coût de la maintenance et sur la fiabilité.

Les méthodes de fabrication ont également conduit à certains choix, en matière de structure, par exemple.

La partie centrale est constituée d'un squelette résistant comportant deux éléments longitudinaux en tôle emboutie qui se prolongent à l'avant par les poutres support de plancher cabine. Ces éléments sont assemblés entre eux par deux cadres pleins, l'un à l'avant constitue la paroi arrière de cabine et l'autre à l'arrière, la paroi avant de soute à bagages.

Ce squelette reçoit en outre, à la partie supérieure, le plancher mécanique, à la partie arrière, la soute à bagages prolongée par la poutre de queue et, à la partie inférieure, les attaches de train à patins.

A part les deux cadres, tous les éléments constitutifs de la structure centrale et avant sont indépendants des formes extérieures. Ils ont donc des formes simples, rectilignes avec des bords tombés à angle droit, ce qui simplifie beaucoup la fabrication.

La forme extérieure est donnée par des capots en matériaux composites sandwich de verre-résine et mousse de remplissage.

La poutre de queue et la soute à bagages sont de formes développables et toutes deux sont constituées d'une tôle roulée sans lisse avec quelques cadres transversaux.

C'est la mise au point des méthodes de fabrication en tôles embouties de grandes dimensions, utilisant des nuances particulières d alliage léger qui a permis la réalisation de la structure du 350 telle qu'elle est aujourd'hui.

C'est également la mise au point des méthodes de fabrication d'éléments de grande dimension en polycarbonate chargé de fibrès de verre coupées et thermoformées qui a permis la réalisation de la verrière, avec quelques pièces seulement, assemblées par soudo-collage.

Au total, la structure de l'Astar 350 ne comporte plus que 300 pièces environ au lieu de 1000 pièces pour l'Alouette II.

La simplification des méthodes ou du travail du contrôle a également conduit à certains choix technologiques.

Pour éviter, par exemple, les sujétions imposées par le contrôle des soudures, celles-ci ont été éliminées le plus possible. C'est le cas du train d'atterrissage où les extrémités de traverse sont épanouies hydrauliquement à chaud pour former la patte de fixation traverse-patin. Il en résulte une meilleure qualité, une élimination des rebuts soudure, une réduction du nombre de phases de fabrication et une économie substantielle.

La modularité choisie pour la BTP facilite aussi le travail du contrôle et les modes d'assemblage choisis tendent généralement à éviter des tolérances de fabrication trop serrées, non seulement coûteuses à réaliser mais aussi coûteuses à contrôler.

L'organisation de la production intervient également dans certains cas pour la définition du produit.

Pour l'Ecureuil, l'organisation en unités autonomes de production pour certains ensembles a orienté la définition vers des solutions ne demandant pas de moyens sophistiqués, impossibles à rassembler pour une petite équipe qui, de plus, ne comporte pas forcément de personnel de très haute qualification.

L'assemblage séparé de tout le groupe moto-sustentateur, beaucoup plus aisé, a nécessité de penser les frontières de cet ensemble en fonction de cet impératif.

Enfin, le Service Approvisionnements joue un rôle important pour le choix, avec le personnel d'Etudes, des organes et équipements qui conviennent, sans recourir systématiquement au lancement de produits spéciaux. Les économies réalisées peuvent être considérables.

Dans le 350 par exemple, c'est un ventilateur automobile deux fois plus léger et trente fois moins cher que le ventilateur aéronautique, prévu initialement, qui sert au refroidissement de l'huile BTP et moteur.

Ce sont également des radiateurs automobiles qui sont utilisés.

La pompe hydraulique d'alimentation des servo-commandes est une pompe industrielle 3 fois moins chère et de masse sensiblement identique.

En outre, une action de réduction de coût, menée avec les fournisseurs, a donné également des résultats intéressants sur les équipements spécifiques de l Ecureuil.

Les essais de qualification ont été faits chaque fois que cela était nécessaire pour la sécurité et le bon fonctionnement de la machine, mais on s'est attaché à n'apporter aucune modification aux équipements industriels choisis, ce qui aurait eu des répercussions importantes sur le prix.

Quels sont les résultats obtenus aujourd'hui ?

Les objectifs de coût de fabrication, fixés au terme de la phase avant-projet, ont pu être révisés en baisse de 10% au moment du lancement de la fabrication série.

La courbe de décroissance des temps pré-établie pour la série a néanmoins été dépassée pour la production des machines produites jusqu'à présent en raison des évolutions de définition intervenues tardivement.

Cependant, aujourd'hui, au 200ème appareil, le temps passé est sur la courbe prévue et on devrait passer au-dessous dans les mois qui viennent.

Le coût de la matière, du moteur et des équipements n'a malheureusement pas évolué de la même manière que le coût des fabrications Aérospatiale, ce qui explique la différence que l'on observe dans la décomposition du prix entre l'AS 350-Ecureuil et une machine produite antérieurement comme le Dauphin AS 360. On peut remarquer l'importance considérable du poste moteur et du poste équipements. Le moteur notamment représente pratiquement la moitié du prix de revient de production.

Une amélioration très nette du coût en utilisation a pu être observée par rapport à celui de l'Alouette II.

Par heure de vol, le coût d'utilisation du 350 est environ 30% plus faible que celui de l'AlouetteII. Comme le 350 a des performances sensiblement plus élevées, c'est en réalité une division par 3 du coût par kg transporté que le 350 peut offrir par rapport à l'Alouette II.

Ces avantages expliquent le succès qu'a rencontré l'AS 350 sur le marché international ainsi que le succès de la version bimoteur de la machine, AS 355, vendus respectivement à 500 et 250 exemplaires aujourd'hui.

Le chiffre des ventes du 355 bimoteur, est d'autant plus remarquable que l'appareil est toujours en développement et que les premières livraisons ne doivent pas intervenir avant la fin 1980.

La cadence de production pour l'ensemble des deux appareils devrait atteindre 40 par mois vers 1982 ....

Les points les plus importants à retenir de cette expérience AS 350-Ecureuil sont les suivants :

1. - la recherche du moindre coût est devenue une obligation pour rester compétitif et améliorer l'efficacité des machines produites,

2. - le bénéfice à attendre d'une recherche systématique de réduction des coûts peut être extrêmement important,

3. - les gains les plus importants sont obtenus dès le stade de la conception initiale en faisant appel aux personnels d'études et de production les plus compétents et les plus expérimentés, rassemblés en nombre limité au stade avant-projet,

4. - cet effort doit être poursuivi pendant toute la phase de développement et d'industrialisation,

5. - cet action doit toucher tous les domaines concernés par la réalisation d'un produit nouveau, la conception, la fabrication (méthodes et organisation), le contrôle, les approvisionnements et même les essais en vol.

6. - la recherche du moindre coût de production doit être menée sans oublier les aspects performances, la masse notamment, et l'aspect coût de maintenance qui contribuent à réduire le coût par kg transporté, et qui constitue, indépendamment du coût d'acquisition, la caractéristique la plus intéressante pour l'utilisateur.

Enfin, tous les avantages obtenus par cet effort de réduction des coûts pour les utilisateurs civils sont également intéressants pour les utilisateurs militaires parce que les budgets d'équipements et de fonctionnement sont limités et que, par ailleurs, un coût d'utilisation réduit implique, de façon certaine, de meilleures performances, une meilleure disponibilité, un entretien réduit, des rechanges moins nombreux, en un mot : u n e   m e i l l e u r e   e f f i c a c i t é.

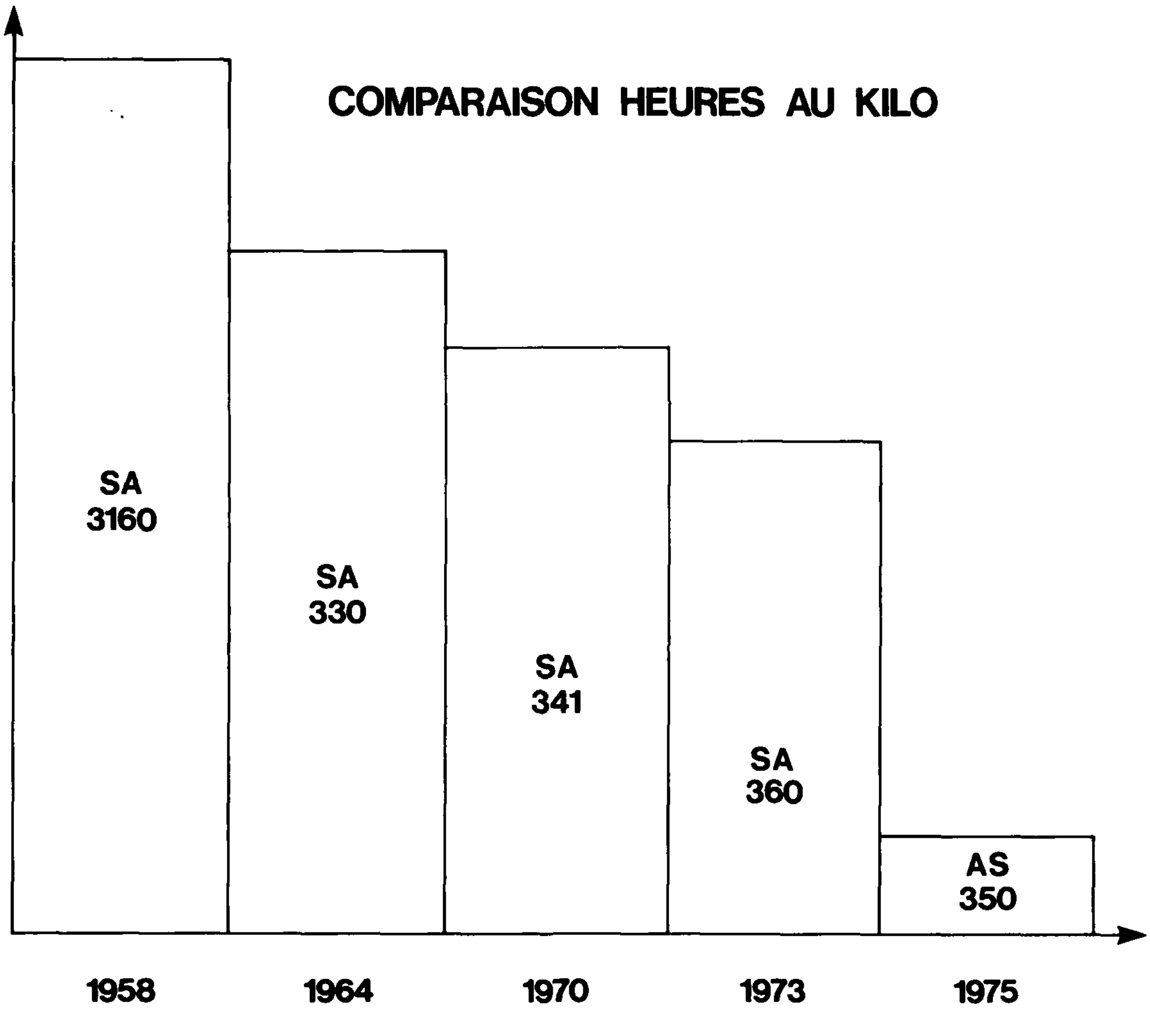


Figure 1

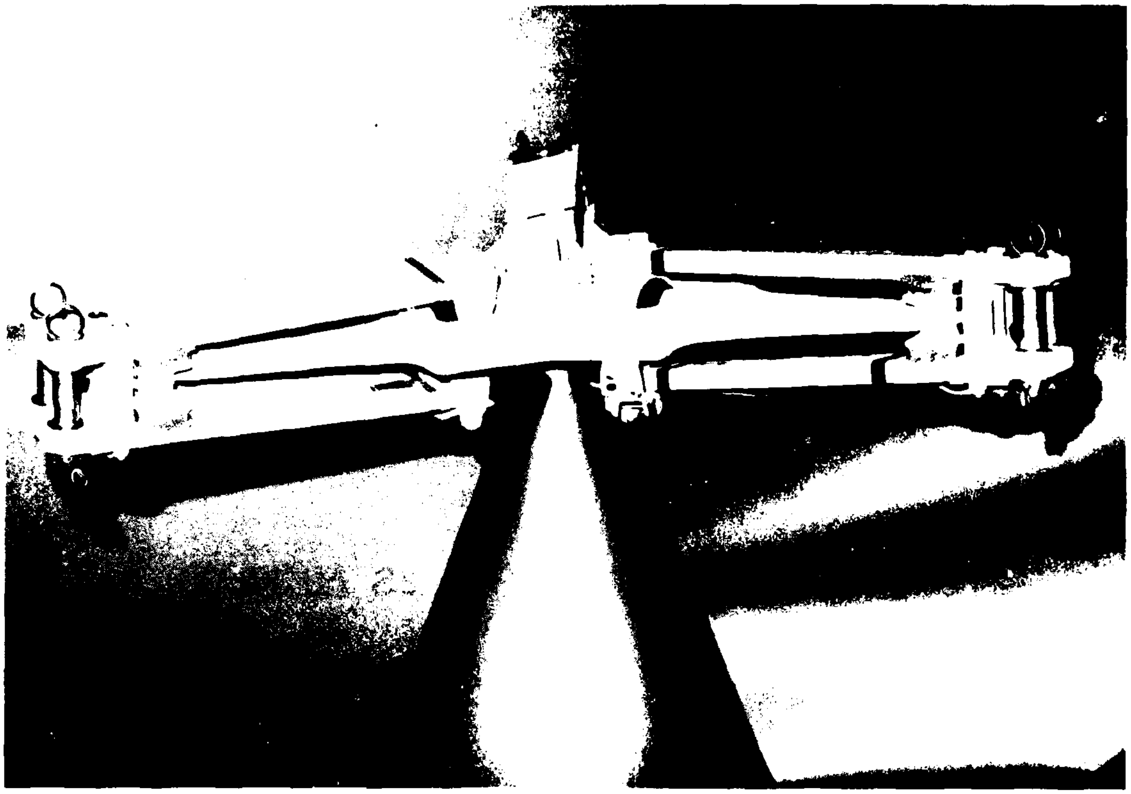


Figure 2

Figure 3

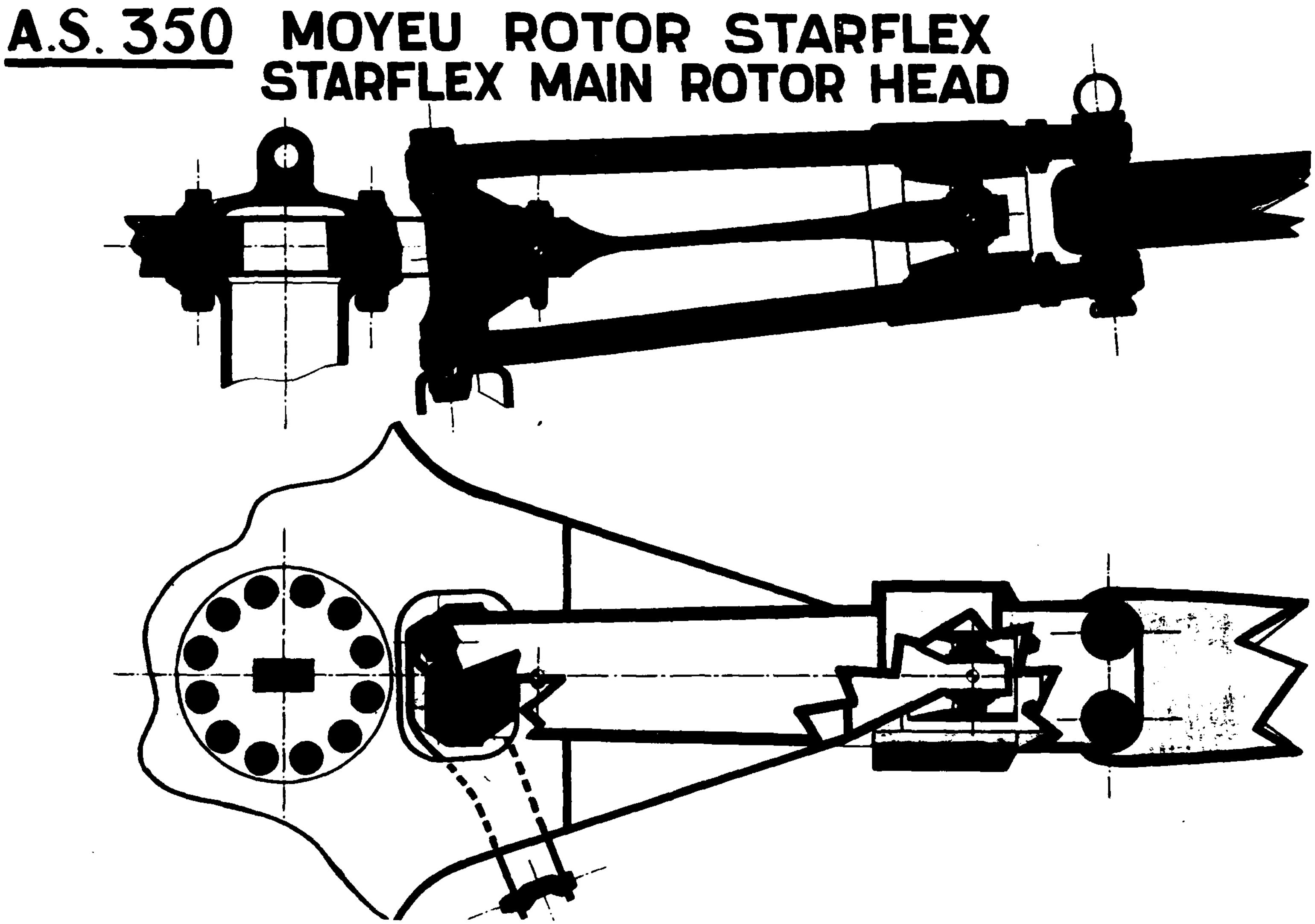
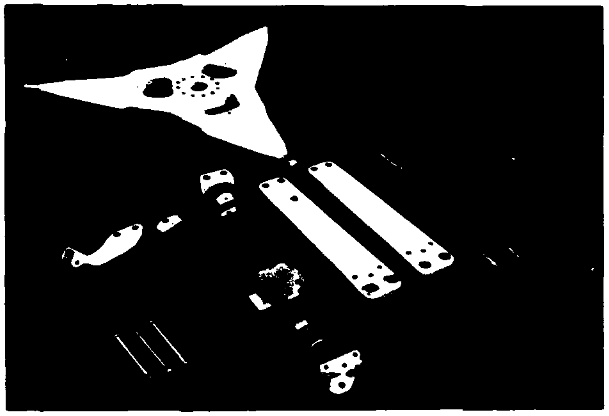


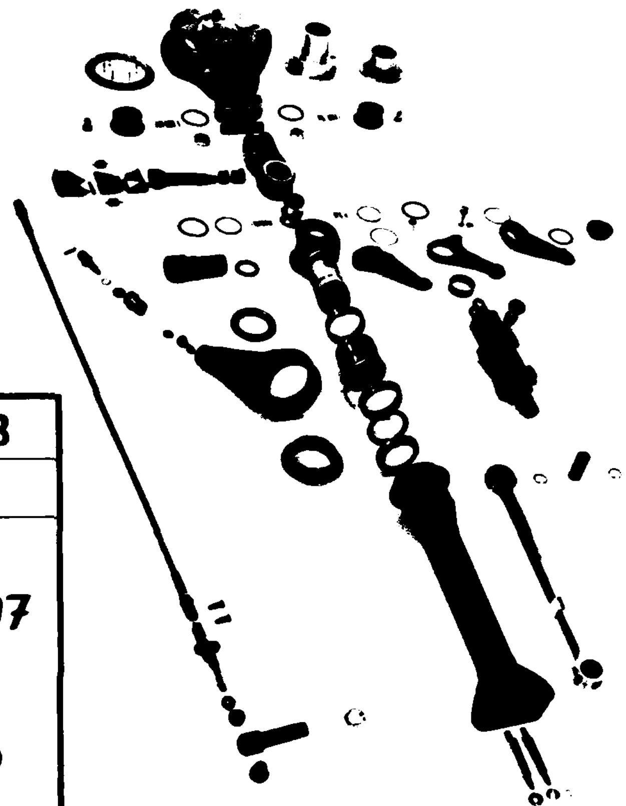
Figure 4

AS.350 COMPARAISON MOYEUX ROTORS PRINCIPAUX

STARFLEX AS 350



SA 318 ARTICULE



NOMBRE DE PIECES		AS 350		SA 318	
TOTAL		70		377	
DONT	ROULEMENTS	0	0	30	97
	JOINTS	0		45	
	GRAISSEURS	0		22	
	PALIERS AUTOLUBRIFIANTS	3	6	0	0
	PALIERS LAMIFIES	3		0	

177

Figure 5

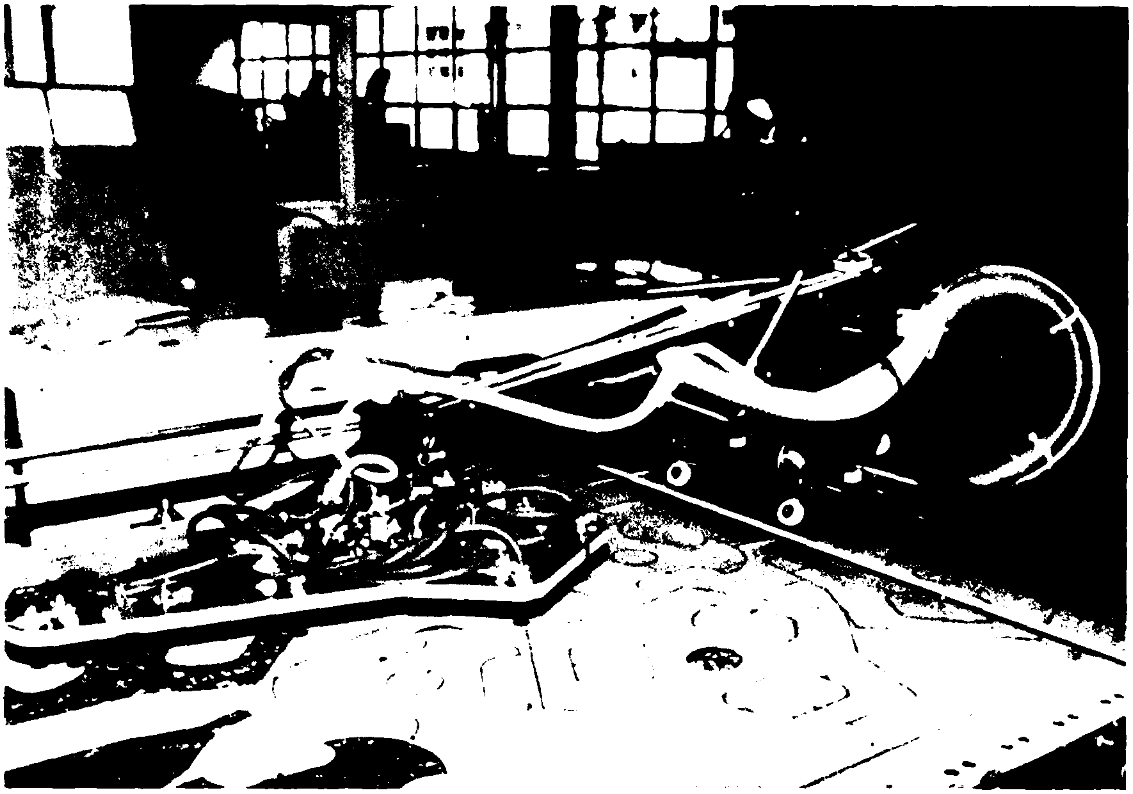


Figure 6

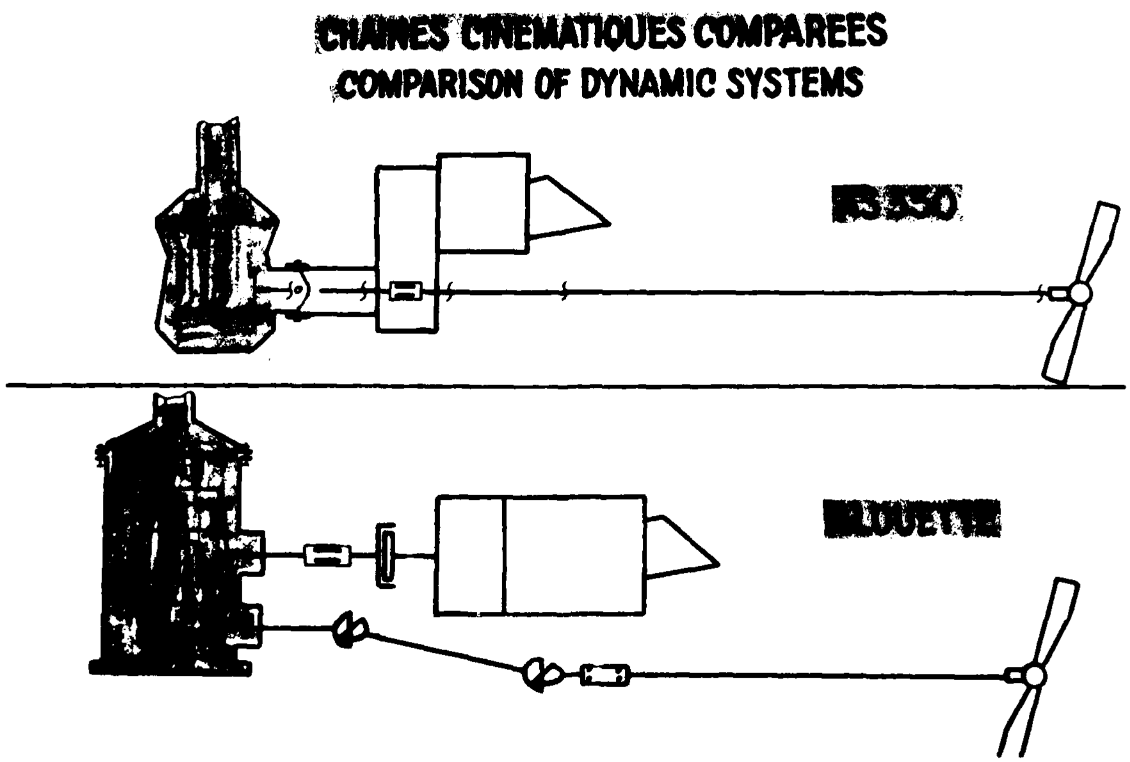


Figure 7

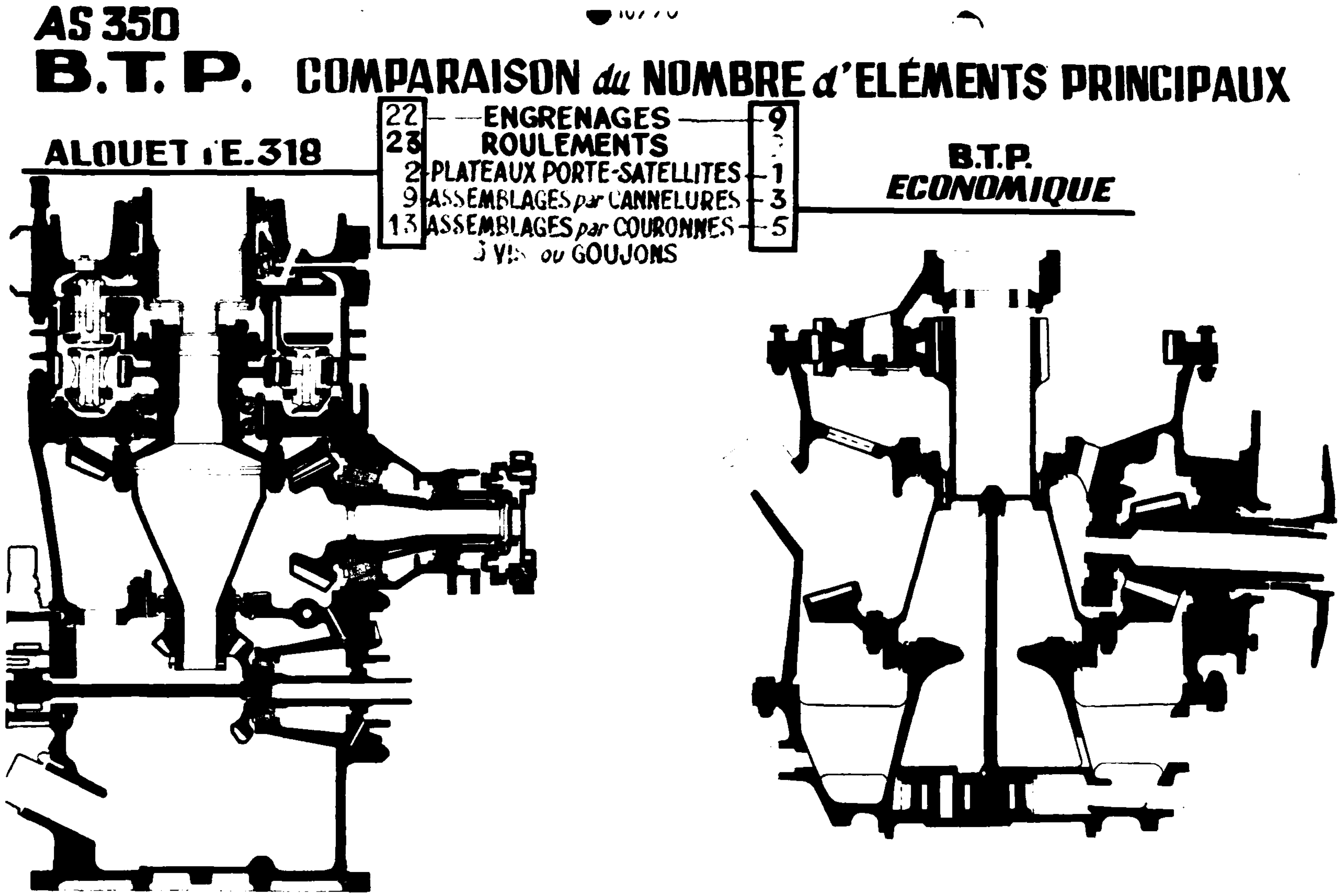

AS 350
B.T.P.
COMPARAISON du NOMBRE d'ELÉMENTS PRINCIPAUX
ALOUETTE.318
B.T.P.
ECONOMIQUE
22 ENGRENAGES 9
23 ROULEMENTS
2 PLATEAUX PORTE-SATELLITES 1
9 ASSEMBLAGES par CANNELURES 3
13 ASSEMBLAGES par COURONNES 5
à VIS ou GOUJONS

Figure 8

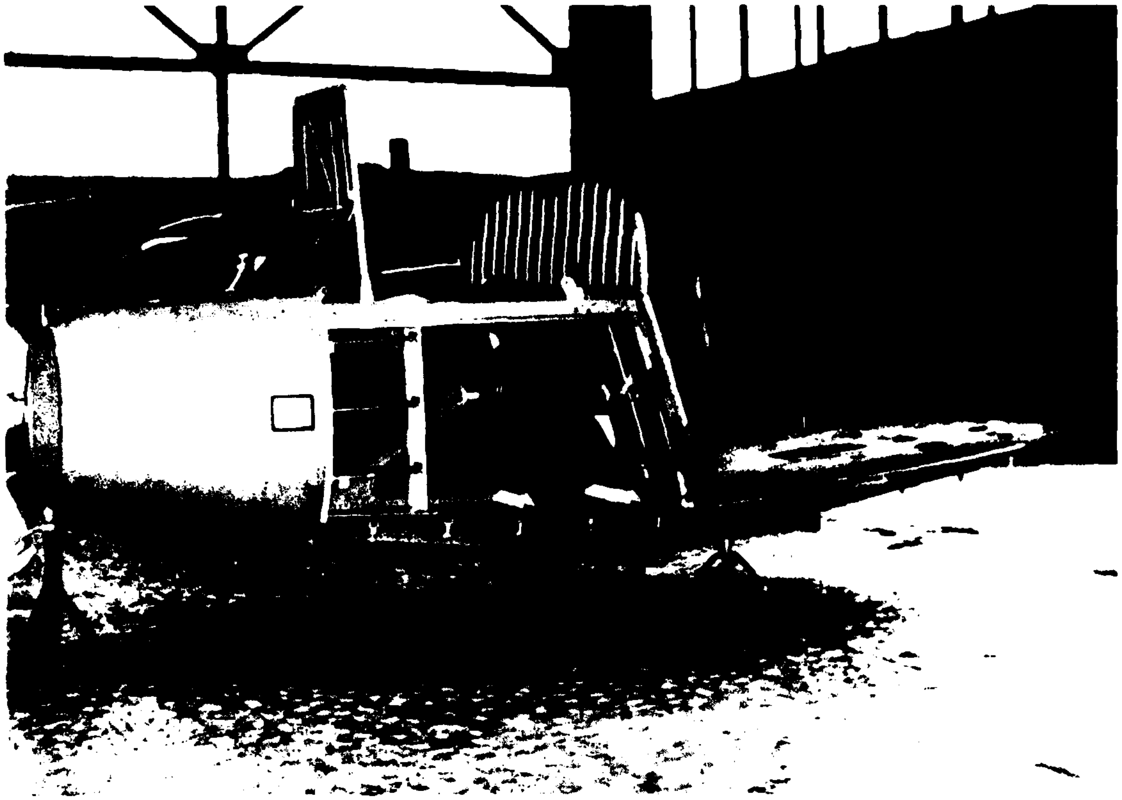


Figure 9

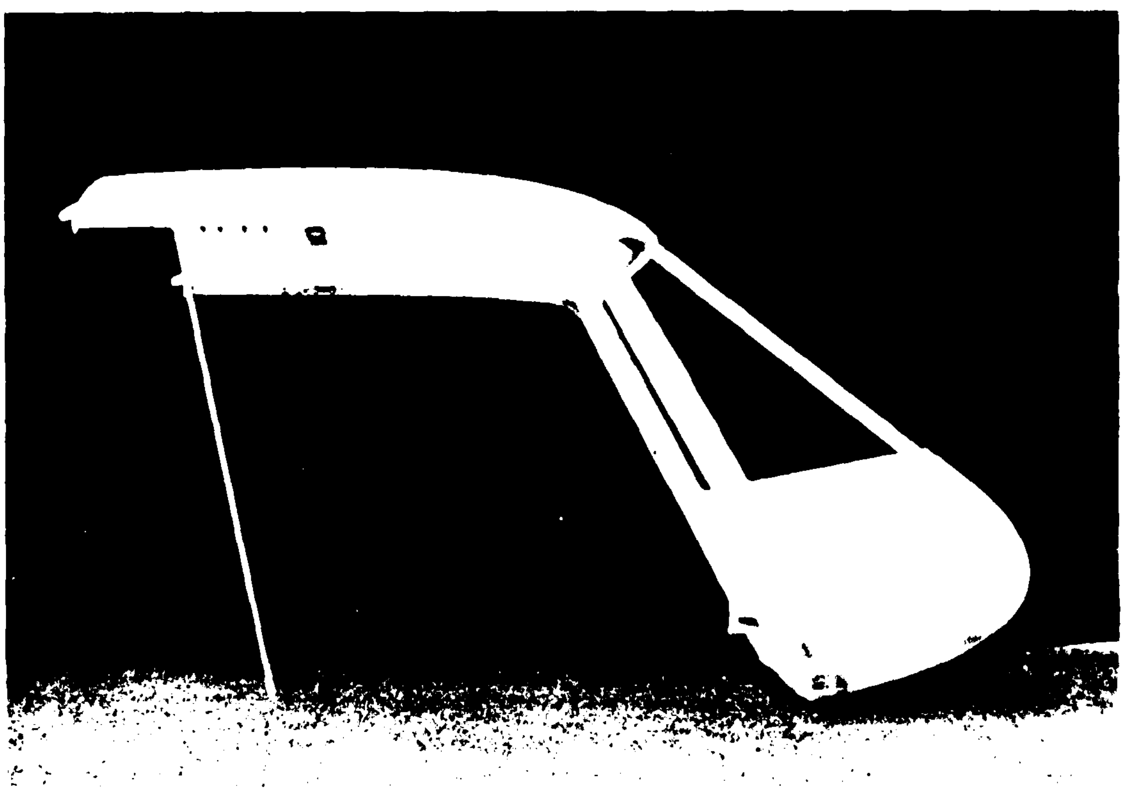


Figure 10

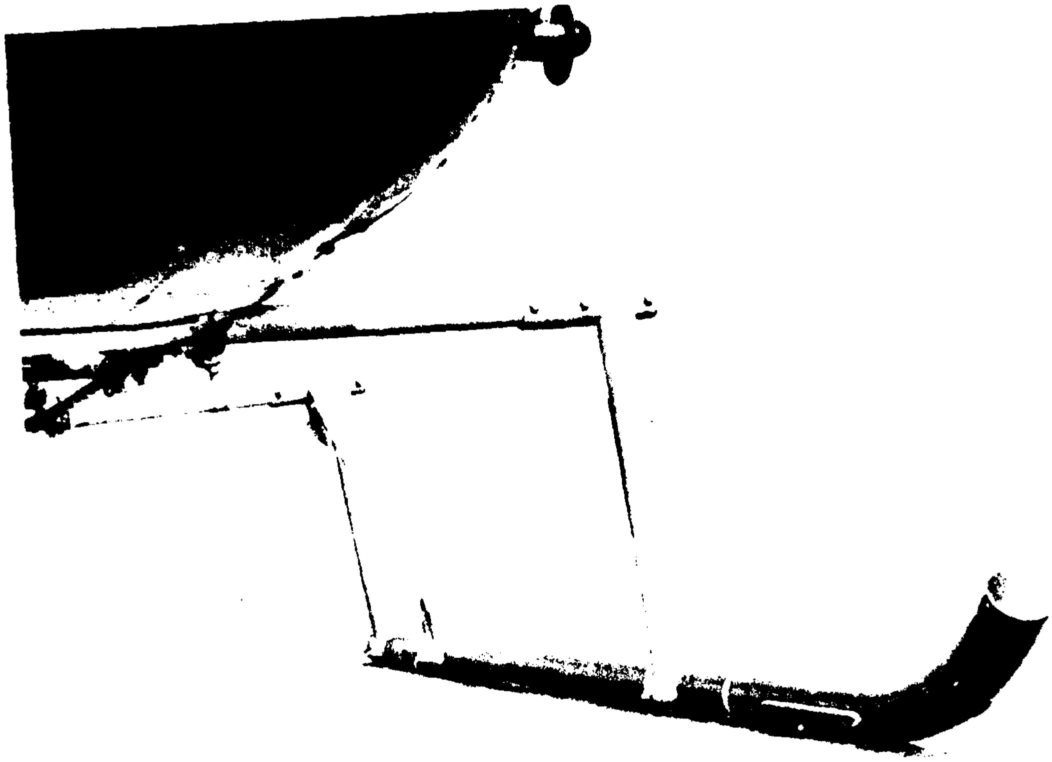


Figure 11

Figure 12

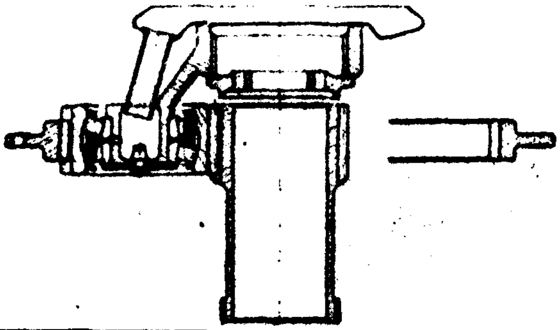
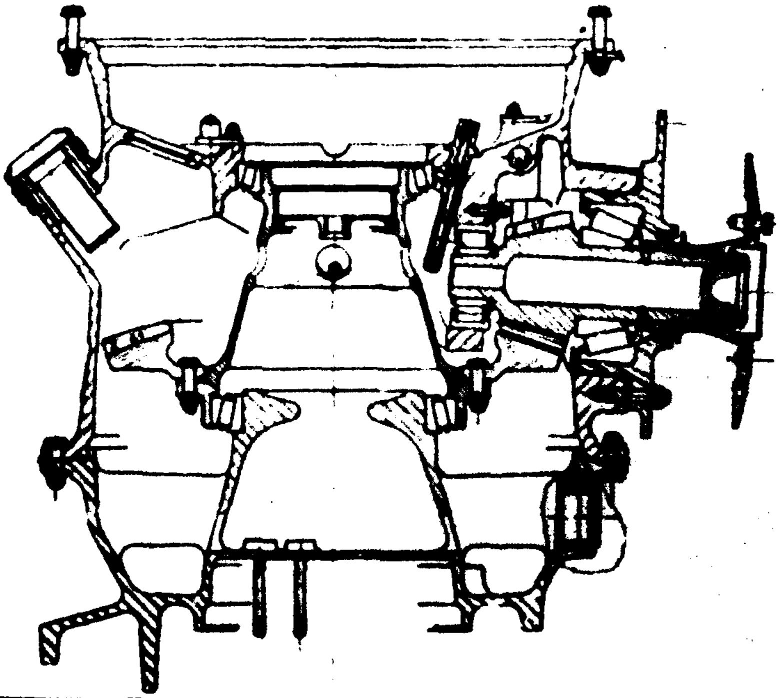
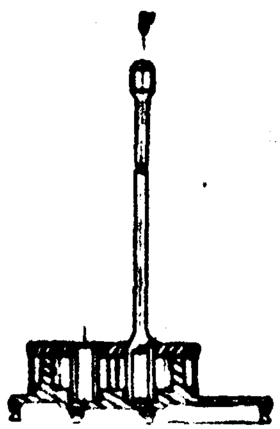
MGB MODULES	TBO
	5000 h
	7000 h
	7000 h

Figure 13

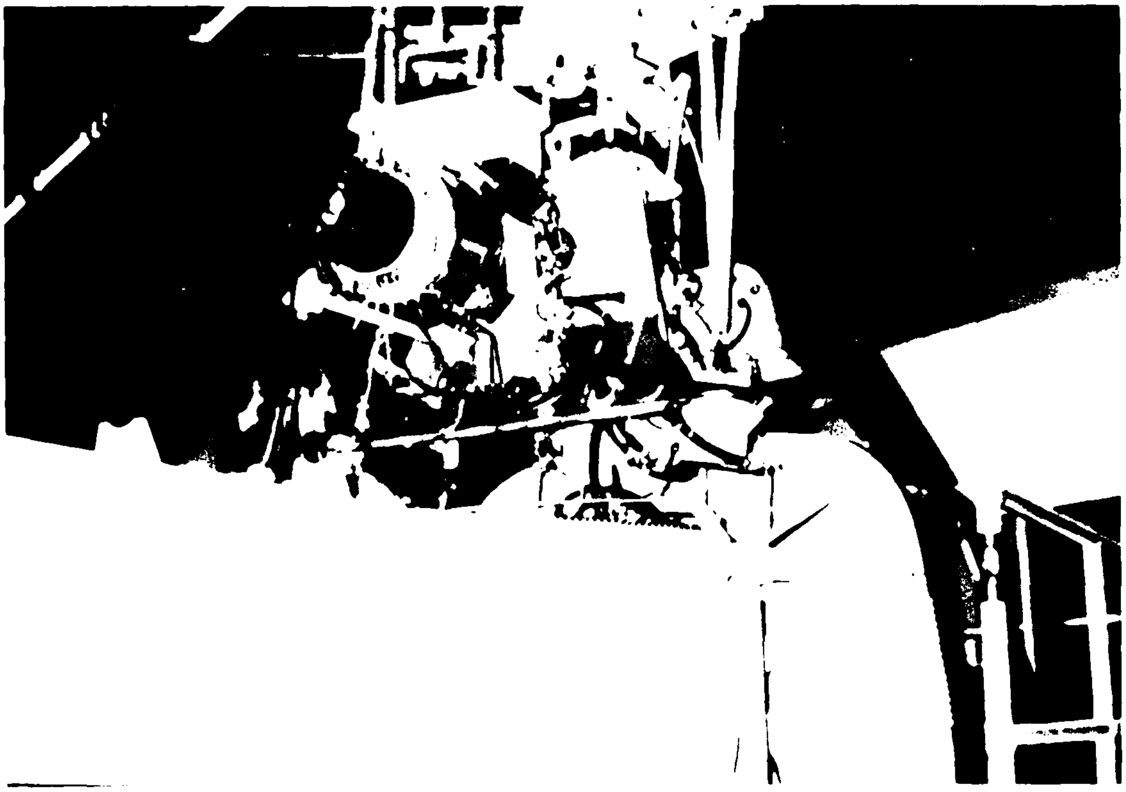


Figure 14

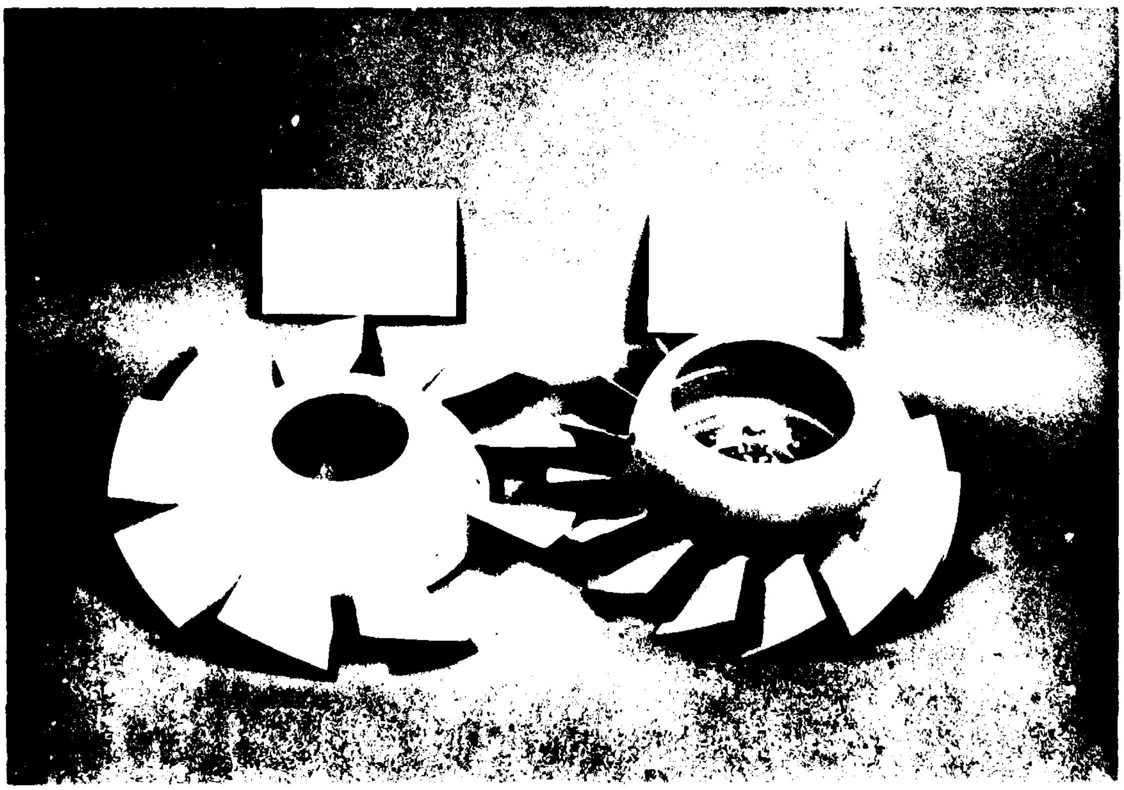


Figure 15

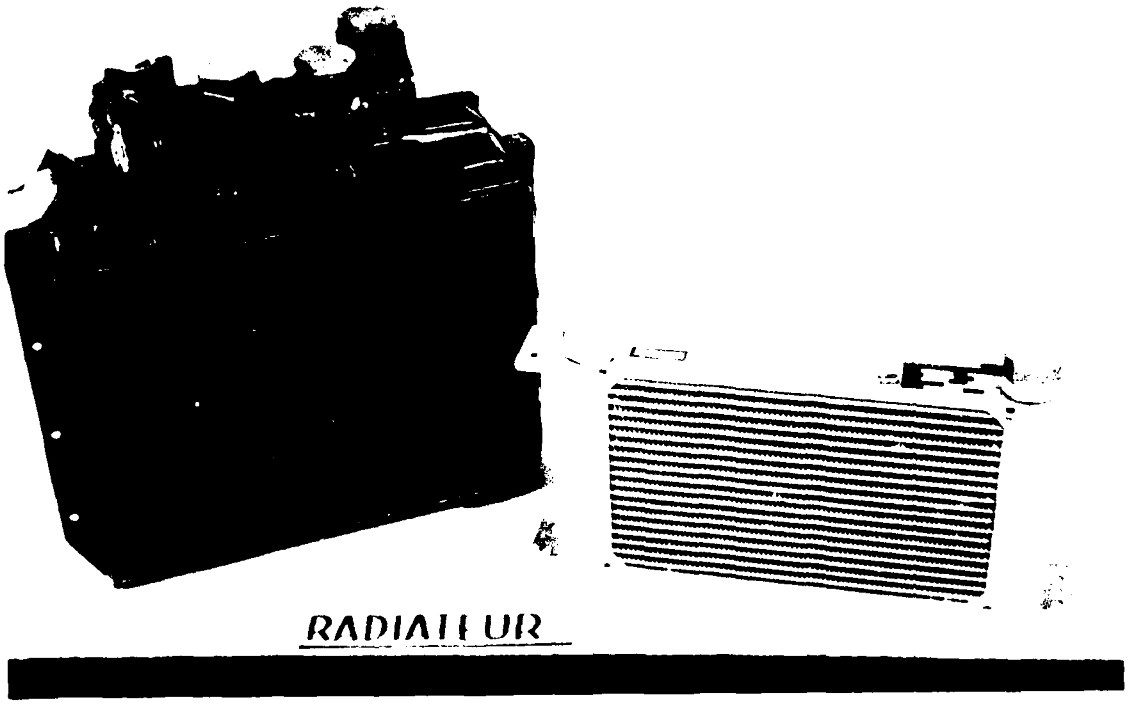


Figure 16

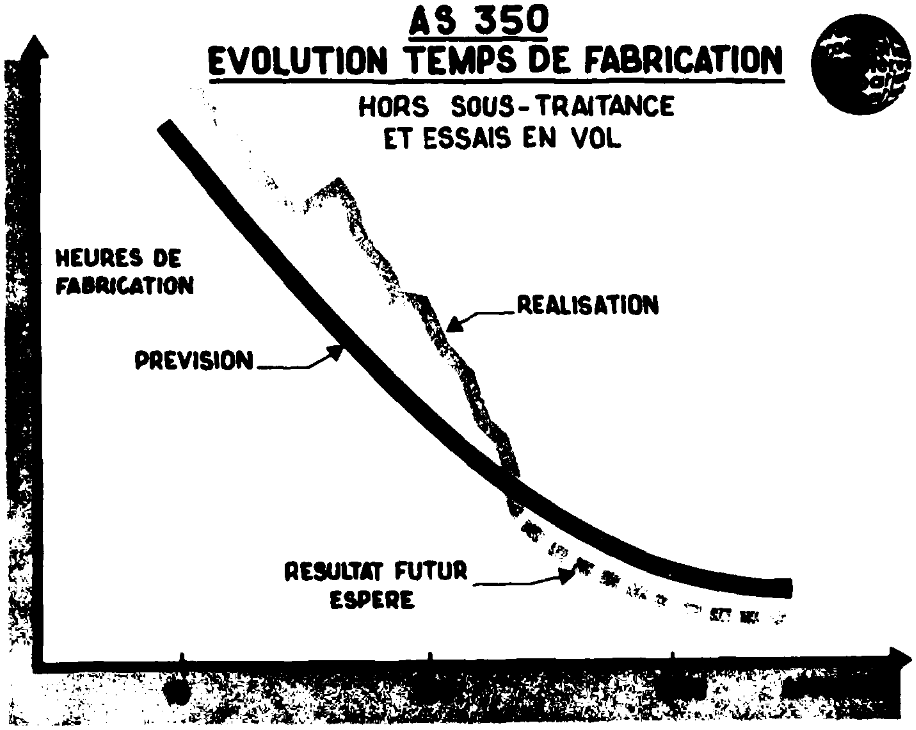


Figure 17

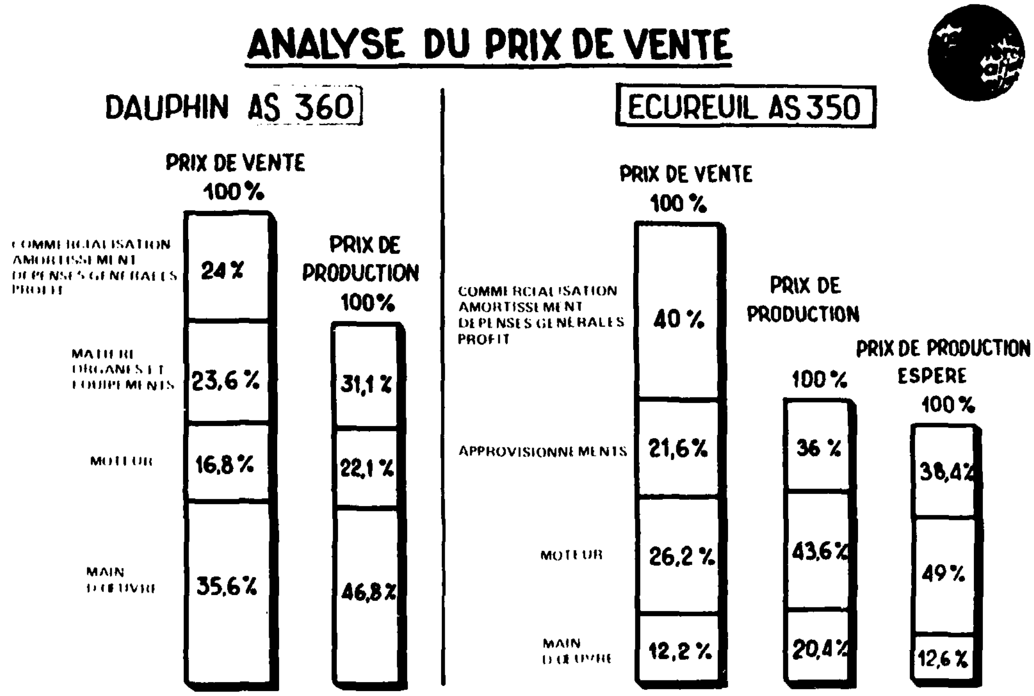

ANALYSE DU PRIX DE VENTE
DAUPHIN AS 360
PRIX DE VENTE
100%
24%
23,6%
16,8%
MAIN
35,6%
PRIX DE
PRODUCTION
100%
31,1%
22,1%
46,8%
ECUREUIL AS 350
PRIX DE VENTE
100%
COMMERCIALISATION
AMORTISSEMENT
DEPENSES GENERALES
PROFIT
40%
APPROVISIONNEMENTS
21,6%
MOTEUR
26,2%
MAIN
12,2%
PRIX DE
PRODUCTION
100%
36%
43,6%
20,4%
PRIX DE PRODUCTION
ESPERE
100%
38,4%
49%
12,6%

Figure 18

RELIABILITY-CENTERED MAINTENANCE

by
F. S. Nowlan
Director of Maintenance Analysis
United Airlines
San Francisco, California, U.S.A. 94128

INTRODUCTION

For many years maintenance was a craft learned through experience and rarely examined analytically. More recently specific aspects of the preventive maintenance process have received intensive analytical treatment. Nevertheless it has been difficult or impossible to use these analytical methods for the development of preventive maintenance programs. Sometimes the analytical models are not representative of real life situations, and in any case the information necessary to implement the methods usually is not available.

The commercial airlines, however, have been successfully working towards a complete understanding of the overall maintenance process and this work has led to the establishment of a logical discipline, called Reliability-Centered Maintenance in the United States, which can be used to develop a scheduled maintenance program that will ensure that an aircraft's inherent design levels of safety and reliability are realized. The discipline always results in a minimum cost maintenance program in light of the reliability information that is available at any given time. The less the information the higher the costs, since some scheduled work will be directed at obtaining reliability information as the airplane ages in service, and other preventive work will be the result of the discipline's default strategy that leads to conservative decisions when the necessary information is lacking.

The use of Reliability-Centered Maintenance principles minimizes the maintenance activity component of life-cycle costs. It also leads to reductions in the inventory support and facilities necessary to cover both preventive and corrective maintenance activities. I believe that joint appreciation of these principles by maintenance and design specialists is essential for development of airplanes which can be more effectively maintained and achieve higher levels of safety and operating reliability.

PROGRAM OBJECTIVES

The objectives of a RCM maintenance program are not peculiar to it. They are the same as those of programs developed by other concepts, namely:

- To ensure realization of the inherent safety and reliability levels of the airplane.
- To restore the airplane to these inherent levels when deterioration occurs.
- To obtain the information necessary for design improvement of those items whose inherent reliability proves inadequate.
- To accomplish these goals at the lowest possible cost, consistent with the highest possible degree of safety, including maintenance costs, support costs, and the economic consequences of loss of mission capability and reduced operational readiness.

The important role of cost-effectiveness in RCM decision making helps to clarify the nature of inherent reliability characteristics.

INHERENT RELIABILITY CHARACTERISTICS

The inherent reliability of an item is not the length of time it will survive without failures; rather, it is the level of reliability the item will exhibit when it is protected by preventive maintenance and adequate servicing and lubrication. The degree of reliability that can be achieved, however, depends on certain characteristics that are a direct result of the design details of the equipment and the manufacturing process that produced it. These characteristics determine both the need for preventive maintenance and the effectiveness with which it can be provided. Thus from a maintenance viewpoint, inherent reliability characteristics are such factors as:

- Failure consequences, judged by the effect of loss of function on safety, mission capability and operational readiness.
- Failure modes which lead to an item's loss of function.
- Exposure to secondary damage that results from certain failure modes.
- Visibility of the failure process and a mechanic's ability to discover potential failures and thereby prevent functional failures.
- Evidence by which the operating crew can realize that a functional failure has occurred.
- Exposure to the consequences of multiple failures.
- Failure rates.

- Relationships between operating age and the likelihood of failure.
- Cost of preventive maintenance.
- Costs of correcting failures.

The test of cost-effectiveness means that an RCM program will not include some tasks which would reduce the likelihood of failures that do not have a direct adverse effect on operating safety. However, when a failure has economic consequences the inclusion of a task that is not cost-effective would merely transfer these consequences from one cost category to another, it would not reduce them. Thus the cost factors on both sides must be considered inherent reliability characteristics since they dictate the level of reliability that is feasible for an existing design. Within this framework the RCM technique ensures all the operating capability of which the equipment is capable. Moreover, it results in a selection of only those tasks which will accomplish this objective; hence it also provides the required maintenance protection at minimum cost.

WHAT MAINTENANCE CAN DO TO ENSURE REALIZATION OF INHERENT CAPABILITIES

When we are developing maintenance programs we must remember that there are only four basic types of maintenance tasks that mechanics can perform to protect inherent safety and reliability characteristics. They can:

- Inspect an item at specified intervals to find and correct potential failures, thereby preventing functional failures. These are called on-condition tasks.
- Rework (overhaul) an item at or before some specified operating age (interval) to reduce the frequency of functional failures. These are called scheduled rework tasks.
- Discard an item or one or more of its parts at or before some specified life limit to avoid functional failures or reduce their frequency. These are called scheduled discard tasks.
- Inspect a hidden-function item at specified intervals to find and correct functional failures that have already occurred but were not evident to the operating crew. These are called scheduled failure-finding tasks.

The first three types of tasks are directed at preventing single failures. The fourth is directed at preventing multiple failures. Although a hidden-function failure has no immediate adverse consequences it does set the stage for a sequence of failures whose consequences may be critical. Certain elevator-control systems, for example, are designed with concentric inner and outer shafts so that the failure of one shaft will not result in any loss of elevator control. If the second shaft were to fail after an undetected failure of the first one, the result would be critical; hence the immediate consequence of any hidden-function failure is increased exposure to the consequences of a sequence of multiple failures.

TASK APPLICABILITY AND EFFECTIVENESS

RCM requires that scheduled tasks be both applicable and effective. Applicability depends upon the reliability characteristics of the item that is subjected to the task. Thus an inspection to detect and correct potential failures, thereby preventing functional failures, is applicable only if the item has characteristics that make it possible to define a potential failure condition. Similarly a scheduled rework task is not applicable unless the likelihood of a functional failure is an increasing function of the operating time since its last rework.

There are specific reliability-characteristic criteria that must be satisfied before any one of the four types of tasks can be considered to be applicable to an item. In the case of an on-condition task:

- It must be possible to detect reduced failure resistance for a specific failure mode.
- It must be possible to define a potential-failure condition that can be detected by an explicit task.
- There must be a reasonably consistent age interval between the time of potential failure and the time of functional failure.

The criteria that a scheduled rework task must meet before it is considered applicable to an item are:

- There must be an identifiable age at which the item shows a rapid increase in failure probability.
- A large proportion of the units must survive to that age.
- It must be possible to restore the original failure resistance of the item by reworking it.

Effectiveness is a measure of the results of the task; the desired results, however, depend on the failure consequences that are involved. For example, we wish to prevent all functional failures that have a direct adverse effect on operating safety, or at least to reduce their likelihood to some acceptably low value. Thus a proposed task might appear useful if it promises to reduce the overall failure rate, but it would not be considered effective unless either singly or in conjunction with other tasks it reduces the probability of failure to an acceptably low value. When safety is not involved effectiveness means cost effective; the cost of performing scheduled maintenance must be less than the benefit of the reduced

failure rates that result from it. Such benefits include reduction in costs of corrective maintenance and inventory, and reduction in costs imputed to operational nonavailability.

The distinction between applicability and effectiveness is usually obvious for inspection tasks. The item either does or does not have characteristics that make such a task applicable, and if it is applicable it will be effective if the interval is short enough. For scheduled rework tasks, however, the distinction is sometimes blurred by the intuitive belief that the task is always applicable and therefore must be effective. In reality imposing an age limit on an item does not in itself guarantee that its failure rate will be reduced. In fact Figure 1 shows that the characteristics of most complex items are such that the failure rate will not be reduced, unless a dominant failure mode is present. The issue is not whether the task can be done, but whether doing it will in fact improve reliability.

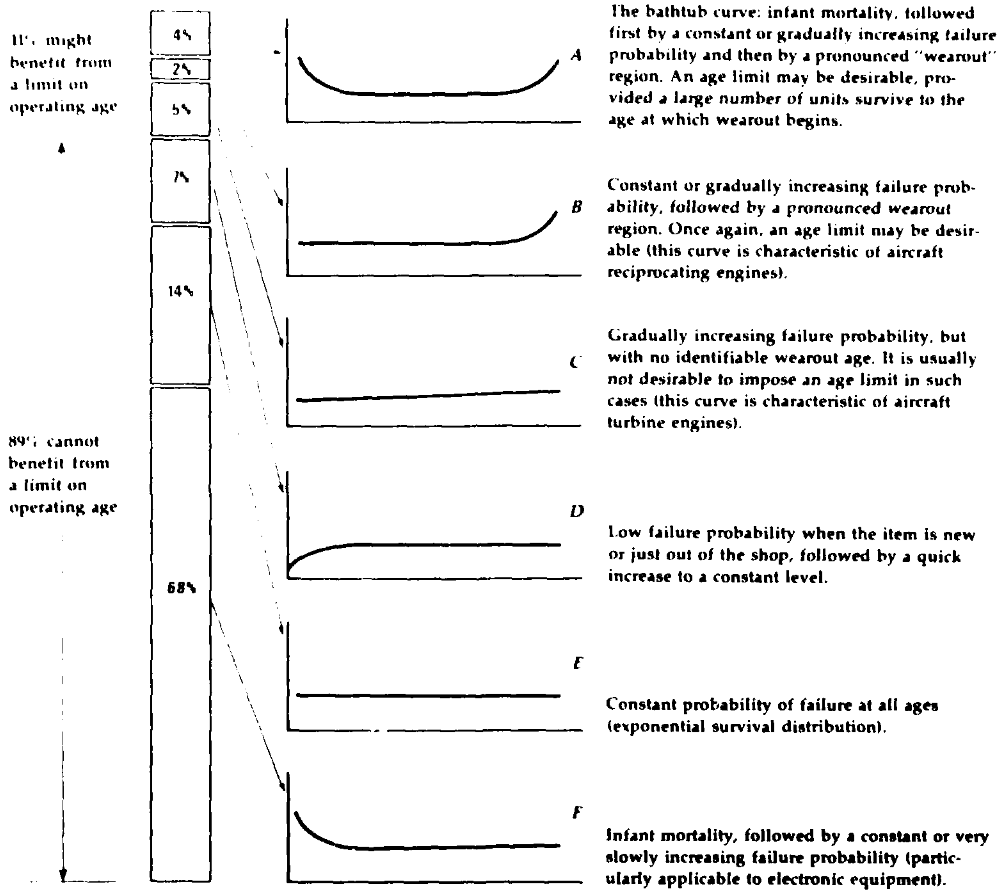


FIGURE 1 Age-reliability patterns. In each case the vertical axis represents the conditional probability of failure and the horizontal axis represents operating age since manufacture, overhaul, or repair. These six curves are derived from reliability analyses conducted over a number of years, during which all the items analyzed were found to be characterized by one or another of the age-reliability relationships shown. The percentages indicate the percentage of items studied that fell into each of the basic patterns (United Airlines)

RELIABILITY-CENTERED MAINTENANCE PROGRAMS

The preventive maintenance program for an airplane consists of the complete set of tasks which will be performed on it and their associated intervals. Since these tasks are prescheduled for accomplishment at defined intervals such programs are often called scheduled maintenance programs. A Reliability-Centered Maintenance program is one which has been developed by a discipline that requires:

- Identification of all functionally significant and structurally significant items on the airplane,

- Assessment of the consequences of failure for each significant item, and identification of any failure modes that might cause critical secondary damage,

- Use of the following criteria for task effectiveness:

    (1) Reduction of failure likelihood to an acceptably low value if failure has adverse safety consequences,

    (2) Cost-effectiveness for evident functions that do not affect safety,

    (3) Assurance of adequate availability for hidden functions, to control the likelihood of an undesirable sequence of multiple failures.

- Assessment of task applicability based upon the reliability characteristics of the affected item.

An airplane's reliability characteristics are established by its design and the manufacturing process that produced it. They are inherent. Maintenance makes it possible to realize them but not to improve them. When safety is not involved the RCM discipline rejects preventive work that could improve an item's reliability if the benefits of the improvement are less than the costs of achieving it. In this case the unimproved reliability is considered to be one of the item's inherent characteristics, and the only way to alter it is to change the design.

It is the explicit use of various reliability factors in maintenance program decision making that resulted in this technique being called Reliability-Centered Maintenance by the United States Department of Defense.

Identification of Significant Items

The development of the initial preventive maintenance program for a new type of airplane begins with a comprehensive review of its design features to limit the size of the project by a quick, approximate but conservative, identification of a set of functionally significant and structurally significant items. A functionally significant item is one where a functional failure could have a direct adverse effect on operating safety, or major economic consequences. The evaluation of failure consequences involves a top down approach. What effect does the failure have on the decisions that will be made first by the operating crew, and then by maintenance personnel.

The assessment of significance makes extensive use of the available failure modes and effects analyses. A default strategy of classifying an item as significant is followed to ensure further study when there is insufficient information to justify a nonsignificant classification.

The primary consideration in determining structural significance is the effect that failure of an element has on the residual strength of the remaining assembly and on the functional capability of the overall structure.

The results of the from-the-top-down partitioning process depicted by Figure 2 have the following properties:

- Any item containing a significant item is itself significant.

- Any nonsignificant item is contained in a higher-level significant item.

- Any lower-level item contained in a nonsignificant item is itself nonsignificant.

In the case of transport airplanes this approach usually results in the identification of several dozen functionally significant items and several hundred structurally significant items. These items require further study to determine the applicability and effectiveness of scheduled maintenance tasks. It is important to note that the approach also identifies the items that have hidden functions, most of which will require consideration in the scheduled maintenance program.

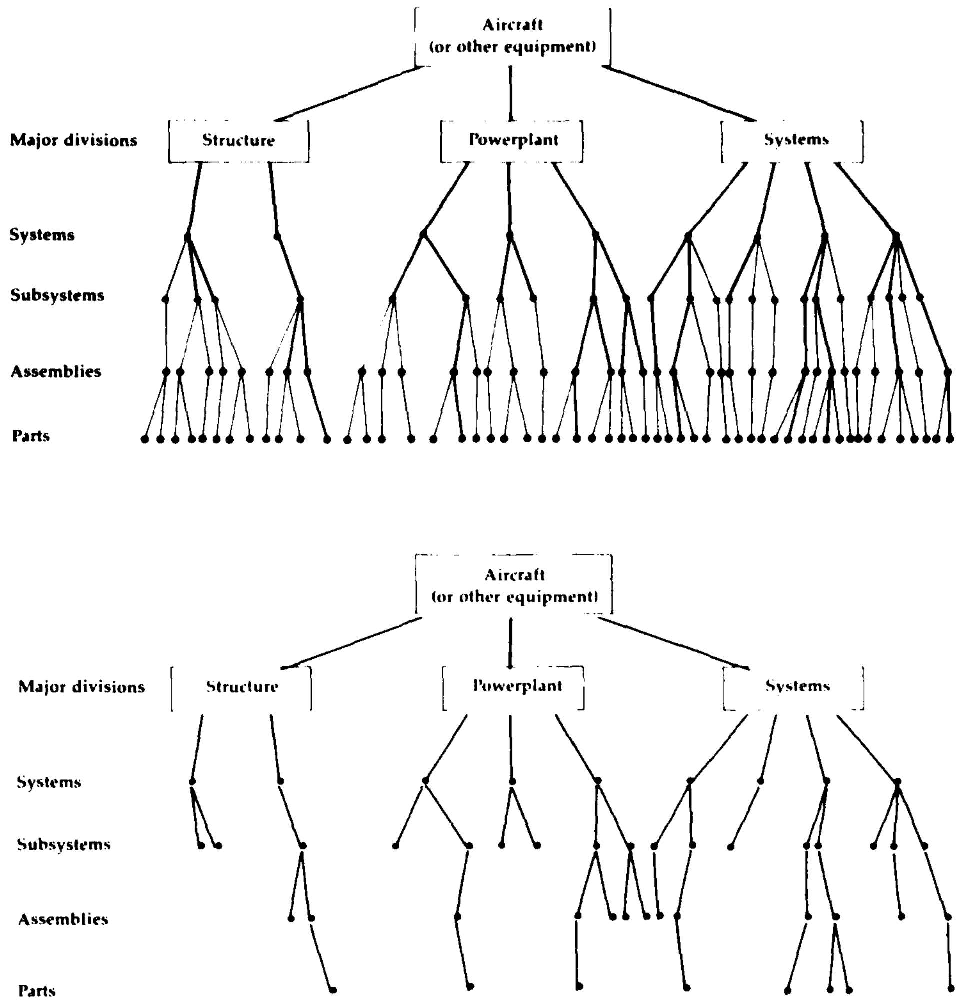


FIGURE 2 Partitioning an aircraft for preliminary identification of significant items. The equipment is first partitioned to show all items in descending order of complexity. Those items whose failure clearly has no significant consequences at the equipment level are then pruned from the tree, leaving the set of items on which maintenance studies must be conducted. Each significant item will include as failure modes all the failure possibilities it contains.

Evaluation of Failure Consequences

The partitioning procedure yields a conservative first approximation of the items that might benefit from scheduled maintenance. Each of these significant items is then examined in detail to determine whether its failure consequences actually qualify as significant - and if so, whether the item can in fact benefit from scheduled maintenance. Even when the significance of an item is confirmed, there may be no form of preventive maintenance that is applicable and effective. Such items cannot be eliminated from consideration, however, without full analysis.

This re-examination of failure consequences leads to the classifications shown in Figure 3 which in turn enable effectiveness criteria to be determined for the various items. If the failure has safety consequences, scheduled maintenance is required to reduce the risk of failure to an acceptable level. If a failure that is evident to the operating crew does not have safety consequences scheduled maintenance is desirable only if it is cost effective. If failures will not be evident to the flight crew scheduled maintenance is necessary to ensure the level of hidden function availability is adequate to control exposure to a multiple failure. In the last case it is necessary to consider the consequences of failure sequences that begin with failure of the hidden function.

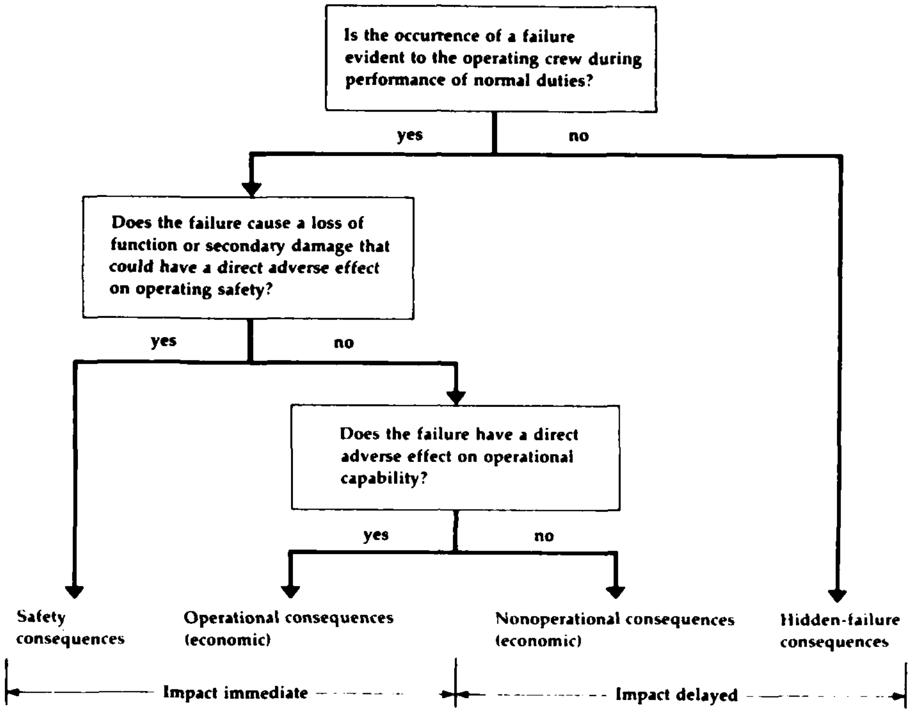


FIGURE 3 Decision diagram to identify significant items and hidden functions on the basis of failure consequences. Failures that affect safety or operating capability have an immediate impact, since the aircraft cannot be dispatched until they have been corrected. The impact of nonoperational failures and hidden failures is delayed in the sense that correction can be deferred to a convenient time and location.

Evaluation of Proposed Maintenance Tasks

The next phase of RCM analysis involves a systematic study of each failure mode of the significant items to determine whether one of the basic maintenance tasks will satisfy both the criteria for applicability and the specific conditions for effectiveness. There is a definite order of preference to our use of preventive tasks which is shown in Figure 4. This in turn controls the sequence of analysis.

On-condition inspections directed at specific failure modes are the most desirable type of task. Since they are based on the feasibility of defining some identifiable evidence of a reduced resistance to the type of failure in question each unit is inspected at regular intervals and remains in service until its failure resistance falls below a defined level - that is, until a potential failure is discovered. On-condition tasks discriminate between units that require corrective maintenance to forestall a functional failure and those units that will probably survive to the next inspection, hence they permit all units of an item to realize most of their useful lives. Thus the costs of both scheduled and corrective maintenance are minimized when on-condition tasks are applicable and effective.

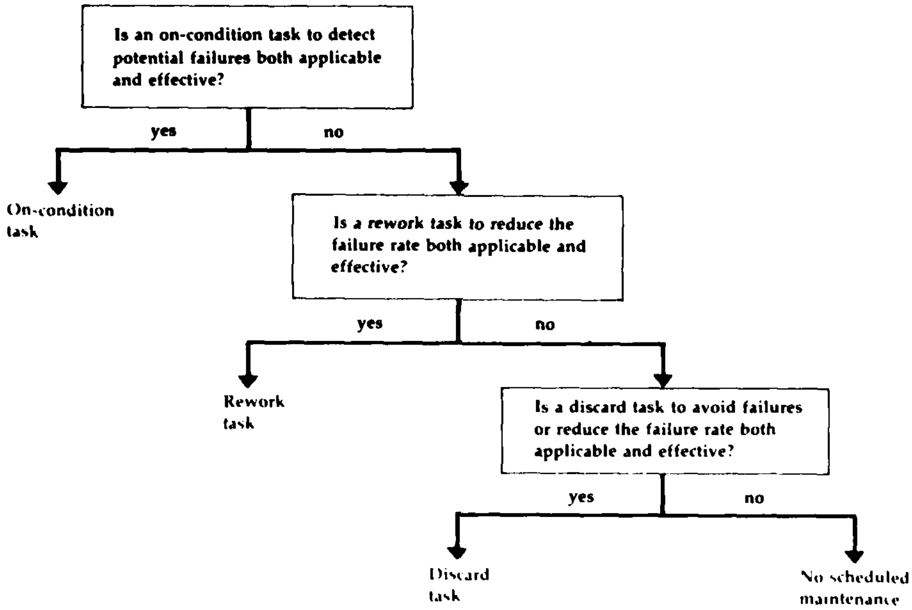


FIGURE 4 Decision diagram to evaluate proposed scheduled-maintenance tasks. If none of the three directly preventive tasks meets the criteria for applicability and effectiveness, an item whose failures *are evident cannot* be considered to benefit from scheduled maintenance. If the item has a hidden function, the default action is a scheduled failure-finding task.

The RCM Decision Diagram

Figures 3 and 4 have been combined in Figure 5 which depicts the entire RCM decision making process for identifying the applicable and effective tasks that should comprise the scheduled maintenance program. Each task in the program is included for a specific identifiable reason related to the reliability characteristics of the airplane.

Failure consequences govern the entire decision process represented by this structured decision diagram, both to establish maintenance requirements and to evaluate proposed tasks. The binary form of the diagram allows a clear focus of engineering judgment on each issue, and it provides the basic structure for a default strategy - the course of action to be taken if there is insufficient information to answer the question or if the program development team is unable to reach a consensus.

The decision logic also plays the important role of specifying its own information requirements. The first three questions assure us that all failures will be detected and that any failures that might affect safety or operating capability will receive first priority. The remaining steps provide for the selection of all applicable and effective tasks, but only those tasks that meet the defined criteria are included. Again, real data from operating experience will provide the basis for adjusting default decisions made in the absence of information.

The net result of this careful bounding of the decision process is a scheduled maintenance program which is based at every stage on the known reliability characteristics of the airplane in the operating context in which it is used. In short, reliability-centered maintenance is an answer to the paradox of modern aircraft maintenance - the problem of how to maintain the equipment in a safe and economical fashion until we have accumulated enough information to know how to do it.

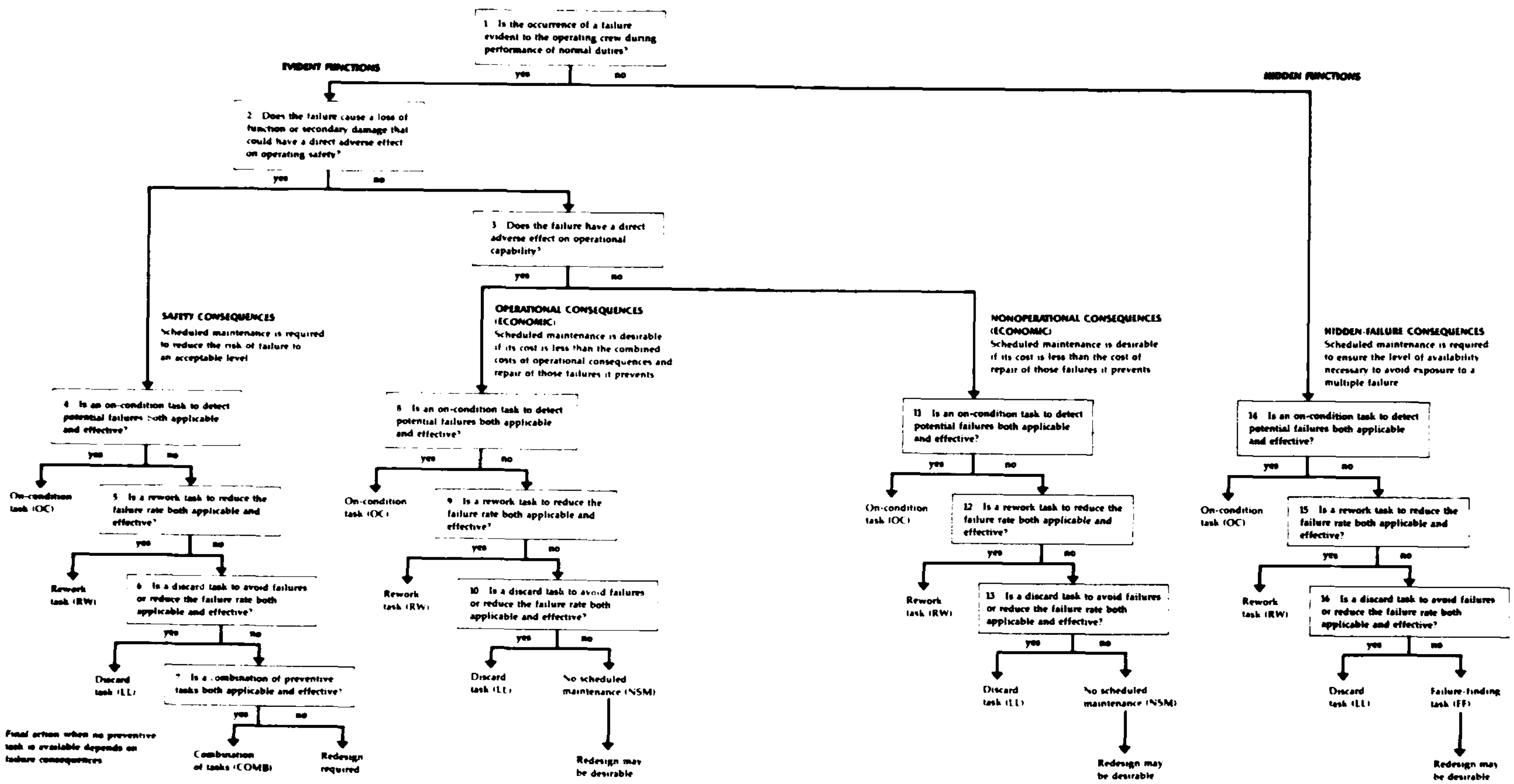


FIGURE 5 The RCM decision diagram. These questions must be asked for each type of functional failure listed for the item. The first three questions determine the consequences of that failure, and hence the objective of preventive tasks. (F. S. Nowlan and H. F. Heap)

The Default Strategy

The information to be channeled into RCM decisions requires analysis under two different sets of conditions. One is the development of a prior-to-service program on the basis of limited information. The other is modification of these initial requirements as information becomes available from operating experience. As information accumulates it becomes increasingly easier to make robust decisions. In developing an initial program, however, there are many areas in which there is insufficient information for a clearcut yes-or-no answer or the development team is unable to reach a consensus. To provide for decision making under these circumstances it is necessary to have a backup default strategy which dictates the course of action in these cases.

The default strategy shows which answer must be chosen for each of the decision questions in the case of uncertainty. In each case the default answer is based on protection of the airplane against serious consequences. For example, in the process of identifying significant items, if it can be demonstrated that the failure of an item has no effect on safety or operating capability, the item can be classified as nonsignificant and does not warrant further study to see if it can benefit from scheduled maintenance. If there is any doubt, however, it must be classified as significant and cannot be dismissed without further analysis. Similarly, if it is not certain that a loss of function will be evident to the operating crew, it is treated as hidden unless a failure mode involves critical secondary damage. A particularly important element of the default strategy is the need for redesign if it is found that no combination of applicable tasks is sufficiently effective to reduce the likelihood of experiencing a specified type of critical failure to an acceptable level.

This default strategy leads to more preventive maintenance than is really necessary. Some tasks will be included as protection against hazards that do not exist, and others may be scheduled far too frequently. The means of eliminating such excessive costs is provided by the age-exploration process which begins as soon as the aircraft goes into service. Through this process the information needed to refine the initial program (and make major revisions when necessary) is gathered systematically for evaluation.

Scheduled rework tasks have little effect upon the overall reliability of complex items, unless there is a dominant failure mode. Hence they are not effective when failures have safety consequences. In any case the failure data required to assess the applicability of such tasks is not available until some time after the airplane has been in service. The same situation exists with regard to discard tasks unless safe-life intervals for them have been established by developmental testing that accurately simulates operational environments. Analyses of cost-effectiveness also require information that must be derived from operational experience. Consequently the default strategy results in a no answer to nearly all questions concerning the applicability and effectiveness of scheduled rework and discard tasks.

A prior-to-service RCM maintenance program, therefore, consists essentially of on-condition tasks, a few safe-life discard tasks, and failure finding tasks for hidden function items; in addition to the usual servicing and lubrication tasks. There will be very few, if any, rework tasks and there will be many items for which there are no scheduled maintenance tasks at all. After the airplane goes into service and additional information on its reliability characteristics can be derived from operating experience the conservatively short initial on-condition inspection intervals will be extended as rapidly as feasible, and it may be found that some items can benefit from scheduled rework and economic-life discard tasks after their applicability and effectiveness can be evaluated.

Major cost reductions result from recognition of the proper role of scheduled rework (overhaul) tasks. Concern frequently is expressed about eliminating scheduled overhauls of such items such as turbine engines, and supporting them instead by on-condition tasks. Let us review some operating experience. Figure 6 exemplifies the premature removal characteristics of an engine that is heavily dependent upon on-condition inspections. It shows the conditional probability of failure of the General Electric CF6 engine installed in one airline's DC-10's as a function of the operating age since the engine's last shop visit. The upper curve shows the total conditional probability for all engines removed for corrective work, and the lower curve shows the conditional probability of functional failures reported by flight crews. It is functional failures that have safety or operational consequences, and the conditional probability in this case is constant. Since the functional failures are independent of the time since engine installation (last shop visit), a rework task is not applicable.

The distance between these two curves at any age represents the conditional probability of potential failures detected by on-condition inspections.

The conditional probability curve that includes potential failures does show an increase with increasing age. However, product improvement by redesign is the proper method of reducing the incidence of potential failures. As it is, shop workload is reduced because each engine remains in operation until a potential failure is detected, and under these conditions there is no increase in functional-failure rate with age.

When it is found necessary to remove an engine for corrective work individual modules are repaired on a selective basis as a result of on-condition inspections. Once again, when a module is repaired the individual piece parts in it are reworked on a selective basis. The engine never receives a traditional type of complete overhaul.

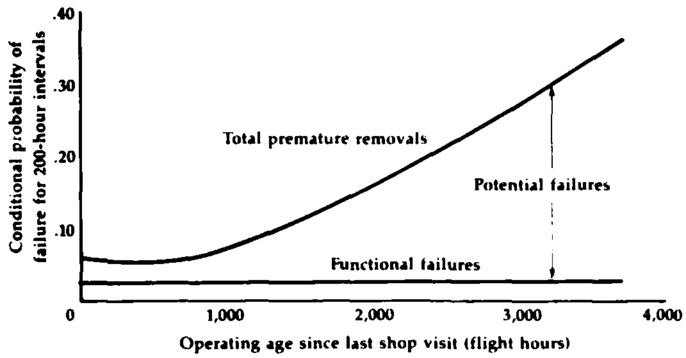


FIGURE 6 Conditional-probability curves for the General Electric CF6-6 engine of the Douglas DC-10. The upper curve shows the total number of premature removals for both functional and potential failures, and the lower curve shows the number of these units removed as functional failures. Although the rate of potential failures increases with operating age, as a result of effective on-condition inspections the functional-failure rate is kept in check and shows no increase with age. (United Airlines)

Age Exploration

The initial program will have tasks and short intervals that were dictated by the default strategy. After the airplane enters service information becomes available about its actual interaction with the operating environment. This information almost certainly contains some surprises - unanticipated types of failures, unexpected failure consequences, unusually high failure rates, or even an absence of anticipated failures. Because the volume of operations is relatively small at first, information is gained at that time about the failures that are likely to occur soonest and with the greatest frequency. As operating time accumulates, the less frequent types of failure are discovered, as well as those that tend to occur at higher operating ages. All this information is used for continuing evolution of the ongoing maintenance program. Such evolution involves updating documented failure modes and effects, and re-evaluation of answers to the decision diagram questions, as well as extension of on-condition intervals.

Any complex equipment is a failure generator, and failure events will occur throughout its whole operating life. The response to these events depends upon failure consequences. If an unanticipated failure has serious implications for safety, information on it is sent at once to the manufacturers and other operators and the first occurrence sets in motion an immediate cycle of maintenance and design changes. In other cases waiting until several failures have occurred allows a better assessment of their frequency to determine the economic benefits of preventive tasks, or possibly redesign. Very often waiting until enough failures have occurred to permit an evaluation of age-reliability relationships provides the information necessary to modify the initial maintenance program.

Evolution of the scheduled-maintenance program does not consist solely of reactions to unanticipated failures. Systematic evaluation of all tasks in the initial program is necessary. On the basis of actual data, the initial conservative intervals for on-condition inspections and hidden function availability checks can be adjusted and the applicability of scheduled rework and economic-life tasks can be investigated. Actual operations will frequently confirm the a priori assessments of failure consequences but occasionally the consequences will be found to be more serious or less serious than anticipated, or a failure thought to be evident to the operating crew is not, and vice versa. The process by which all this information is obtained is called age exploration, both because the amount of information is a direct function of the age of the equipment in service and because some of this information relates to the ages of the items themselves.

Information systems must be established to retrieve and store this information. The generation of some of it will be automatic, such as loss of function events that are evident to the flight crew. In other cases it will be necessary to ensure that the initial program contains tasks that will generate the required information. This is particularly true with regard to on-condition inspection programs for the powerplant and the structure. The ability to measure reduced failure resistance can be assessed at the time of the initial program but not the age at which the reduction will first become evident or its rate of deterioration as items age in service. Hence the initial inspection intervals are established at conservatively short values to force the age-exploration which will generate information that can be used to establish longer more appropriate intervals. Rapid use of age-exploration information as it becomes available is essential to increase the conservative initial intervals of on-condition inspections of powerplant and structural items and thereby avoid unnecessary maintenance costs. Conversely age-exploration may indicate that a more intensive inspection program is necessary after items have reached high total times.

PRODUCT IMPROVEMENT

In the course of evaluating the maintenance requirements of complex equipment it will be found that there are many items that cannot benefit from scheduled maintenance, either because there is no applicable preventive task or because the available forms of prevention cannot provide the level of reliability necessary. Some of these problems result from the compromise decisions the designer made, since the requirement for lightness and compactness in high performance aircraft is in direct opposition to the weight and bulk that is necessary for strength and maintainability. The exposure to problems is increased when the designer is working with new components and materials whose characteristics have not been proved by experience. Consequently the identification of reliability problems during early operations and development of design changes to correct them is really part of the normal development cycle of high performance equipment.

Product improvement directed toward better reliability takes a number of forms. An item may be modified to prevent critical failures, to eliminate a particularly expensive failure mode, or to reduce its overall failure rate. The airplane, or an item on it, may be modified to facilitate replacement of a failed unit, to make a hidden function visible, to incorporate features that make on-condition inspections feasible, or to add redundant features that alter the consequences of failure.

Hence the information obtained from age-exploration must be used not only to refine the preventive maintenance program but also to direct cost-effective product improvement efforts.

DESIGN-MAINTENANCE PARTNERSHIP

The large life-cycle cost reductions that can be achieved by use of reliability-centered maintenance principles require a joint effort of both the designer and the maintenance man. On one hand, the design of the airplane establishes its inherent reliability characteristics, including the consequences of functional failures as well as the methods and costs required to prevent them; on the other hand, scheduled maintenance attempts to preserve all the safety and operating reliability of which the airplane is capable. Designers have not always understood the capabilities of scheduled maintenance and the practical limits on these capabilities. By the same token, maintenance organizations have not always had a clear grasp of the design goals of the airplanes that they maintain.

During the development of prior-to-service programs the identification of significant items and hidden functions depends upon the designer's information on failure effects, as well as the operator's knowledge of their consequences. At this stage the information on anticipated failure modes and their associated mechanisms must also come from the designer. While the maintenance members of the program development team will be able to draw on prior experience with similar materials, design practices, and manufacturing techniques, this information must be complemented by the designer's advice concerning the ages at which various forms of deterioration are likely to become evident, although it will be necessary to confirm this advice by age-exploration information. The designer's advice is even more important when new materials and techniques are involved.

At a more fundamental level, it is important for the designer to bear in mind some of the practical aspects of scheduled maintenance. In general, on-condition inspections are the most effective weapon against functional failures. However, it must be possible to use them, preferably without removing items from their installed positions on the airplane. Thus the designer must not only help to identify the items for which such inspections are applicable, but also must make sure that there is some means of access to the area to be inspected. An equally important factor is the use of design features such as the damage tolerant structure that is widely used in transport aircraft, and of materials which result in relatively slow deterioration of items intended for on-condition inspection.

After the airplane enters service it will experience unanticipated failures, some of which require immediate action. In these cases the designer's help is crucial in developing new interim scheduled tasks that will control the problem until design changes can be developed and incorporated in the operating fleet. Both the design and maintenance organizations must work together to identify the failure mechanism involved, because this information is needed for product improvement as well as to develop the interim tasks. Such product improvement entails a two-way flow of information; the operating organization must identify the need for an improvement, and the manufacturer must advise the operator of the results of his continuing test programs and the experience that other users of the equipment have encountered. The development of airplanes that can be more effectively maintained and achieve still higher levels of safety and reliability depends on a continuing close partnership, with both design and maintenance organizations familiar and sympathetic to each other's problems and goals.

EXAMPLES OF COST REDUCTIONS

Although the RCM technique is a considerable expansion and refinement of practices that have been employed by commercial air carriers, I think it is appropriate to exemplify some of the cost savings that have resulted from those airline practices.

The initial maintenance program for the Douglas DC-8 included scheduled overhaul requirements for 339 different items, only eight items had such requirements for the Boeing 747. The result has been a large reduction in the flow of items through repair shops for scheduled overhauls, that at best had little positive effect upon their operational reliability. Reduction of this flow has led to corresponding reductions in shop labor and material costs and the inventory costs of the spare units that were required to cater to that flow.

Turbine engines how have design features that permit extensive use of on-condition inspections and most airlines have been able to eliminate scheduled overhauls of turbine engines. This elimination of the

scheduled overhaul process has enabled the number of spare engines required to cover shop activities to be reduced by as much as 50 percent, or more. With engines costing two or three million dollars each such inventory savings are very large. Increased knowledge of maintenance requirements and the role of on-condition tasks not only has reduced the volume of engines flowing through the shop, it has also led to major reductions in the costs incurred by each visit. Nevertheless engines still account for at least half of an airline's maintenance costs.

Better understanding of structural maintenance requirements for the damage-tolerant structure of transport airplanes and improved use of the information obtained from age-exploration programs have also led to large cost reductions. One airline expended only 66,000 manhours on major structural inspections of the Boeing 747 prior to establishing an initial inspection interval of 20,000 hours. In contrast traditional maintenance policies led to its expenditure of over 4 million manhours before the same interval was attained for major structural inspections of the smaller and less complex Douglas DC-8.

CONCLUDING REMARKS

The problem of basing a preventive maintenance program on an airplane's reliability characteristics might appear to be a lack of the very information that is needed. In reality the problem is not the lack of information; rather, it is knowing what information is necessary in order to make decisions.

The RCM solution to this problem is a structural decision process based, not on an attempt to estimate the reliability of each part, but on the consequences of functional failures for the airplane itself. The decision process thus proceeds from the top down, first to identify those items whose failure is significant on the airplane level and then to determine what scheduled maintenance can do for each of these items. At each step of the analysis the decision is governed by the nature of the failure consequences. This focus establishes the priority of maintenance activity and also permits us to define the effectiveness of proposed maintenance tasks in terms of the results they must accomplish. Once this determination has been made, we are in a position to examine each of the four possible forms of preventive maintenance to see which tasks, if any, are both applicable and effective for the item under consideration.

The process of evaluating failure consequences and maintenance tasks is facilitated by a decision-diagram technique which employs an ordered set of priorities - in the case of both failure consequences and task selection - with the questions at each level worded to define the information required for that decision. In many cases the answer will be obvious from engineering expertise, the manufacturer's test data, and previous experience with similar items. However, in developing a prior-to-service maintenance program a strategy is required for decision making when the appropriate information is now available. Thus the decision logic also provides for default answers to meet this situation. For an item subject to critical failures the default path leads ultimately to redesign where the consequences of failure are economic, the default decision may be to do nothing (no scheduled maintenance) until operating experience provides the information required to justify some other choice.

The result of an RCM analysis is a preventive maintenance program that includes all scheduled tasks necessary to ensure safety and operating economy, but only those tasks that will do so. Where there is no basis for determining whether a particular task will prove applicable and effective, the default strategy provides the most conservative answer, and as the maintenance program evolves, these initial decisions are systematically modified on the basis of actual operating data. This process continues throughout the service life of the equipment, so that the decision structure provides an optimal program in terms of the information available at any time.

The technique described in this paper is a considerable expansion and refinement of the techniques described in such airline industry documents as MSG-2: Airline/Manufacturer Maintenance Program Planning Document published by the Air Transport Association on March 25th, 1970, and ESMG: European Maintenance Systems Guide to Developing Initial Maintenance Programs for Civil Air Transport published by the Association of European Airlines during March 1976.

These principles have been successfully applied to commercial aircraft. However, the RCM decision process itself is general and applies to any complex equipment that requires a maintenance support program designed to realize maximum operating reliability at the lowest cost.

The major obstacle to implementation of the RCM process is the tendency to rely on traditional concepts of scheduled maintenance, especially the belief that scheduled overhauls are a universally effective weapon against failures. Thus an organization must recognize and accept the following facts before it is prepared to use RCM principles:

- The design features of the airplane establish the consequences of any functional failure, as well as the cost of preventing it.
- Redundancy is a powerful design tool for preventing complete losses of function to the airplane.
- Scheduled maintenance can prevent or reduce the frequency of complete losses of function (functional failures), but it cannot alter their consequences.
- Scheduled maintenance can ensure that the inherent reliability of each item is realized, but it cannot alter the characteristics of the item.
- There is no "right time" for scheduled overhauls that will solve reliability problems in complex equipment.
- On-condition inspections, which make it possible to preempt functional failures by potential failures, are the most effective tool of scheduled maintenance.

- A scheduled-maintenance program must be dynamic; any prior-to-service program is based on limited information, and the operating organization must be prepared to collect and respond to real data throughout the service life of the equipment.

- Product improvement is a normal part of the development cycle for all new equipment.

Until an operating organization is comfortable with these facts it may be difficult to proceed confidently with the results of RCM analysis.

The technique that I have discussed today is defined in great detail in a textbook coauthored by Howard Heap of United Airlines and myself. This book, *RELIABILITY-CENTERED MAINTENANCE* can be obtained from the National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161. It is also available from the Defense Documentation Center, Alexandria, VA 22314. Its acquisition number is AD A066579.

SOME ENGINEERING ASPECTS OF LIFE CYCLE COSTING

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SUMMARY

Unlike some branches of accounting, Life Cycle Costing involves many different disciplines including the basic engineering of the aircraft. Engineering forms an important aspect of acquisition costs, operational costs and support costs.

The constituents that are common to most Life Cycle Cost methods are identified and ways discussed in which some of the engineering costs can be minimised. The extra cost of better engineering design may increase the acquisition cost but this will be more than offset by the large reduction in support costs complemented by the increase in reliability and aircraft availability.

Examples are given showing typical contributions to high support costs of mechanical components. In many cases, these costs are avoidable by more care at all stages of design, production and operation of the equipment.

1. INTRODUCTION

Life Cycle Costing is a method of forecasting the cost of future events. The successful forecaster has always had an honourable place in society, even as long ago as the Egyptians priests and the Biblical prophets. It has always been possible to predict events which depend on the laws of physics. This was simply a case of evaluating the law and applying it to the data. Such forecasting can be highly accurate, as in the case of eclipses of the sun and moon. All events depending on physical laws should be forecast with such accuracy. However, difficulties often arise in measuring the data on which the forecast is based, e.g. the times and heights of tides depend basically on the laws of gravity, but can be considerably modified by the local meteorological conditions. In theory, meteorological conditions are wholly predictable, since they depend on known laws of physics. Weather forecasting illustrates one important aspect of successful forecasting, i.e. the baseline from which the forecast is made must be known accurately. In the case of weather, all parameters that affect the weather must be known simultaneously on a global basis. Since this is impossible, the accepted approach to the problem is to monitor the weather at selected points, extrapolate the data to cover intermediate points and then continuously update the forecast. We can all draw our own conclusions on the success rate of this method. Life Cycle Costing has many similarities with weather forecasting. The success of the forecast appears to be inversely proportional to the time interval over which the forecast is required and is dependent on the accuracy of the baseline data. Unfortunately, Life Cycle Costing is also degraded by being dependent on the laws of probability rather than the laws of physics. Also, alas, Life Cycle Costing is affected by the policies of politicians and governments. Such policies can wildly distort the extrapolations on which Life Cycle Costing is based.

In order to assess the credibility of the Life Cycle Cost forecast, it is therefore very important to define accurately the data on which the forecast is based and the constraints that have been applied to the extrapolation from the data.

It is not the intention of this paper to criticise all the different methods of Life Cycle Costing. Instead, items that are common to most models will be identified and ways discussed in which some of the engineering costs can be minimised.

2. THE CONSTITUENTS OF LIFE CYCLE COSTS

Life Cycle Costs can be split into three main constituents :-

1) Costs of Acquisition

2) Costs of Operation

3) Costs of Support

It is impossible to treat these completely separately as there are interactions between them which are usually, but not necessarily, unfavourable, e.g. an item that has the cheapest acquisition cost may have the highest support cost. However, it is the aim of Life Cycle Costing to find a suitable mix of all three ingredients that will give the lowest overall total cost. Let us examine each one, and its interactions, from an engineering point of view.

3. ACQUISITION COSTS

At present these are largely minimised by using the mechanism of the market place. For complete aircraft, the acquisition cost is compared with that of similar aircraft and assessed according to the task that the aircraft is required to do. For commercial aircraft this tends to be different for each route flown and since most airlines require their aircraft to fly more than one route some form of compromise is inevitable. Military aircraft are more specialised and are usually designed to do one task very well or a few tasks as well as possible. In recent years, mainly due to the high costs of buying and maintaining small quantities of specialised aircraft, there has been much more interest shown in multi-role types. However, even in the latter case, the acquisition costs have largely been determined for given tasks by

the state of the art at the time that the design was frozen.

When we look at individual mechanical system components the picture is much clearer, since they have evolved relatively slowly. An aircraft engineer from the 1950's would have little difficulty in recognising a modern fuel pump, hydraulic jack or heat exchanger. Most of the improvements have come from better materials and improved manufacturing methods. If inflation is discounted, this has resulted in lower costs for the same specification or a better specification for the same cost. In general, the airframe manufacturer will choose the cheapest and lightest component on the market if he has sufficient faith in the manufacturer's ability to meet the specification and deliver on time. This favours the component manufacturer with the most efficient design and production teams. A small company could be at a disadvantage if it has to sub-contract some of the production processes to specialist firms over which it has not adequate control. We have found several examples of high support costs that can be traced back to inadequate quality control at the manufacturing stage.

3.1 Design and Development Costs

The acquisition cost can be divided into two parts :-

1) Design and development

2) Production

For military aircraft, design and development costs can be very difficult to assess with a high degree of accuracy. We require the latest technology which will in most cases be unproven and hence an unknown quantity. Unless similar equipment already exists, we have no data baseline from which to extrapolate our costs. This can have unfortunate financial results, as Rolls Royce found out with the use of carbon fibre reinforced plastic fan blades for the RB 211. Few aircraft companies can afford to risk their own money in innovative areas these days and new developments are very closely geared to government's Defence budgets.

It is always difficult to strike the right balance between design costs and testing costs. Economies in one are often more than offset by extra costs incurred in the other. Unfortunately, there are nearly always external pressures to economise on both. Comprehensive test programmes are often difficult to justify, particularly where everyone is convinced in advance that they know what the outcome is likely to be. The designer is reluctant to ask for large scale testing since he feels that his design is the best possible (if not the only) solution to the problem and the money would be better spent seeking solutions to the problems for which he has not yet found answers. Production managers are easily convinced of the logic of this, since they know that if something fails on test it will result in re-design or modifications with the resultant delays on their production time scales. However, this latter philosophy should be strongly resisted. Experience has shown in nearly all cases that the sooner a design error is rectified, the cheaper the solution is found to be. Retrospective modifications to a complete fleet of aircraft have always proved to be a very expensive exercise. Unjustified economies in design are always offset by vastly increased support costs.

Until recently, there has been a tendency to incorporate the latest state of the art in every new design. Unfortunately, each new advance seems to be more expensive than the one it replaces. We should now question very carefully whether we really need the sophistication that is available for the particular role that the aircraft will play. Is an inertial navigator really essential or would a cheaper system using say, a satellite interrogator be sufficient? In many cases equipment is now available that is more accurate and sophisticated than is necessary for a particular aircraft role. If a bomb is capable of devastating an area of 500 square kilometres, do we really need to deliver it with a CEP accuracy of 10 metres? Designers must not forget that safety, accuracy and reliability are really relative terms rather than absolute and that both under and over-specifying can be expensive. The more complicated a component is, the greater are the extra components required to maintain its safety and reliability. What is a realistic price to pay for accuracy and convenience? For intercepting enemy aircraft or missiles, the answer is probably that the highest accuracy possible is essential, but for civil use where the problem is the opposite i.e. to avoid intercepting the path of any other aircraft, the accuracy need only be better than the separation which is considered to be safe.

3.2 Production Costs

A baseline for predicting production costs is usually easier to define than one for design and development costs. In most cases, the type of engineering required is defined at the preliminary design stage. Once a design material has been agreed, the techniques for shaping it into the final product evolve relatively slowly and, as long as aircraft continue to be made from aluminium alloys, the basic processes of casting, forging, machining and riveting are unlikely to change drastically. The use of fibre reinforced plastics is increasing fairly slowly and a production cost baseline is reasonably well established. In the avionics field, production costs depend greatly on the number of components and the sophistication of the techniques involved and this is an area in which changes can occur very rapidly. The increasing cost of software which was almost negligible a few years ago has introduced a new variable into avionics costs which in future will be even more difficult to forecast accurately.

4. COSTS OF OPERATION

These are the costs incurred whilst the aircraft is flying. The major costs are those of fuel, oxygen, expendable armament, and the manpower required to operate the aircraft efficiently and safely. The direct manpower costs of pilots and crew are relatively easy to evaluate, but there are other indirect manpower costs involved as well, such as radar operators and air traffic controllers, which are less easy to quantify. For civil aircraft most of these ancillary costs are included in landing fees, but for military aircraft they have to be included as part of the overhead costs of aircraft operation.

The cost of fuel is one of the most difficult items to forecast. For civil aircraft, the cost to the airline includes all the ancillary costs of supply and storage, which are borne by the oil companies and are reflected in the price per litre. For military aircraft, the costs of fuel include not only the direct cost of the fuel itself, but all the logistic costs of storing and supplying it as well. These include the costs of storage tanks, their protection against the environment and enemy action, specialised fire fighting equipment and refuelling bowsers. These costs are also linked to the price that an air force is prepared to pay for aircraft availability. To illustrate this consider the costs of acquiring and operating a refuelling bowser. Suppose it takes 15 minutes to refuel a long range bomber. If the bomber is required to fly one mission per day a time of 150 minutes to refuel 10 aircraft from 1 bowser may be reasonable. However, for an interceptor aircraft a turn round time of 10 minutes may be required, hence if it takes 5 minutes to refuel 1 aircraft, 5 bowsers are required to refuel 10 aircraft. Hence aircraft availability becomes more important than minimum cost.

Operating costs are very dependent on the number of hours flown per year. These can be very accurately forecast for civil aircraft that are flying known schedules but military aircraft hours are less predictable. They can be affected by such diverse factors as changes in defence budgets, changes in aircraft roles, changes of government and changes in overseas commitments.

5. COSTS OF SUPPORT

Increasing most characteristics of an aircraft e.g. speed, range, maximum altitude, etc., increases the Life Cycle Cost but an increase in Reliability or Maintainability should result in a decrease in support costs. This may be partly offset by an increase in acquisition costs but on balance there is likely to be an overall reduction in Life Cycle Costs. Let us now examine in more detail how good engineering can result in increased Maintainability and Reliability.

5.1 Maintainability

During the design stage of an aircraft it is normal to carry out a Reliability appraisal of all components. Using this as a basis, the components with the greatest expected unreliability should be the most accessible. It is very difficult to convince a designer that his equipment is likely to be unreliable and that it will require frequent adjustment or replacement. There is a tendency to believe that every component is a "Fit and Forget" item. The designers of engine pods have managed to overcome this attitude and, in general, the accessibility of podded engines is very good. On some aircraft it is quicker to change an engine than an internal fuel tank.

The maintainability philosophy of the aircraft should be decided at an early point in the design stages and related to the skill levels that will be available. There has been a tendency for required skill levels to increase and become more specialised. This has the effect of increasing support costs and in order to offset this, more and more specialised test equipment is being used for fault diagnosis. It will always be cheaper to diagnose and rectify a fault in situ rather than to replace a suspected component and rectify it at second line.

It is now possible to fit more built in test equipment on the aircraft, which can not only register that a fault exists, but can also pinpoint with greater accuracy which component is faulty. This will make a marked reduction in diagnostic time and will prevent the removal of components that are subsequently tested at second line and found to be fault free. Many manhours are wasted at present because adequate test equipment is not available at first line. Rectification is often by a system of "trial and error" based on experience. An investigation into first line manhours taken to rectify faults in various mechanical components showed that there was a very wide scatter in the results. If the target manhours were 15, the actual manhours ranged from 1 to 220 with an average of 60 (measured over a two year period). This was typical for most mechanical components and means that actual servicing costs were 4 times the expected costs. The reasons behind this are not clear, but contributory factors include low skill levels, poor or non-existent diagnostic equipment, poor accessibility and artificial means of measuring the attainment of target levels.

Once again, we are brought back to the question, "What price are we prepared to pay for aircraft availability?" On the present system, a reduction in support costs means also a reduction in aircraft availability. Although availability is difficult to quantify in monetary terms, for civil aircraft the ratio of flying time to downtime is a measure of revenue earning capacity which is downgraded by any increase in downtime. For military aircraft, availability is of prime importance and any aircraft out of action is a liability. Turn round time whether for flying defects or major servicing is at a premium and a balance has to be struck between good availability and high support costs.

"What can the designer and customer do to alleviate this situation?" One major area that will repay investigation is that of the increased use of built in test equipment or on-board health monitoring. As more and more of the conventional mechanical systems are replaced and re-organised by electronic management systems, (Is Lockheed's "all-electric" aircraft proposal to be regarded as the ultimate goal?), we have a golden opportunity to use the information generated by such management systems to monitor each component of the system. Any deviation from their expected performance can be instantly compared with that in the aircraft's computer memory and signalled to the pilot or stored for read-out on the ground. Performance degradation can be monitored and preventative maintenance carried out at a convenient time between scheduled flights, instead of waiting until a defect actually occurs. A small start in this direction has been achieved by the use of fatigue meters and engine vibration recording on existing aircraft, but in future aircraft, incorporating on-board energy management systems by microprocessors, the addition of a small amount of extra recording capacity will pay large dividends in the form of increased availability and reduced maintenance.

Having come to terms with all these compromises and alternatives we shall achieve an estimated cost of maintainability. This can be averaged over the aircraft life to produce a cost per flying hour. On what basis do we decide if this is a reasonable figure? For civil aircraft we can compare it with the

costs for the aircraft that it will replace in the fleet and this will probably be accurate enough for our purposes, particularly in the case of major airlines who seldom keep a new aircraft until it is scrapped. In spite of the large number of DC - 3 aircraft still flying, it is certain that few, if any, are still in the hands of their original owners. The situation for military aircraft is different. Most spend their whole lives in one air force and the majority exceed their design lives by a considerable margin. The British Aerospace Canberra was conceived in 1945. It is highly probable that those that are being re-conditioned now will still be flying at the turn of the century. If Life Cycle Costing is to be realistic it must be continually updated throughout the life of the aircraft. A Life Cycle Cost estimate made at the time of a feasibility study will be inaccurate in 10 years time when the aircraft enters service. A fore-cast is only as good as the data on which it is based. If the data change it is important to update the forecast.

5.2 Reliability

The Mean Time Between Failures (MTBF) is a strong cost driver in Life Cycle Costing. Any decrease in Reliability is immediately reflected in a corresponding increase in support costs. Worthwhile increases in Reliability can most easily be achieved if Reliability is regarded as one of the important parameters at the early design stage. A small increase in design costs can produce dramatic increases in Reliability. In general, designers are not as reliability - conscious as they could be. They are motivated far more by performance, weight, cost and safety. A large re-education programme is required to demonstrate how expensive, in terms of support costs, an unreliable product can prove. An increase in Reliability need not necessarily involve penalties in other parameters. A detailed investigation into mechanical system reliability has shown that most causes of unreliability can be eliminated by relatively simple design changes. However, customers' resistance to design changes is very high. Once a design has been translated into hardware the customer is faced with a decrease in aircraft or component availability, a possible increase in spares stocks to cover those in the modification loop (stocks may already be low because of the unreliability) and a large increase in documentation and identification to cover the various modification states of his equipment. This customer resistance increases with time until a point is reached at which the customer decides that it is more economical to live with his unreliable equipment than to modify it. However, this decision is based on the customer's estimate of the aircraft's life and we have already noted that this can be wildly inaccurate. The moral here is that Reliability should be very high on the designer's list of priorities. Unfortunately, the inherent reliability of a design is a very difficult quantity to measure, except with hindsight. Tables exist that quote the random failure rates of similar components. Our investigations have shown that actual failure rates can differ from random failure rates by a factor of 100 or more, since most failures in unreliable equipment are not random, but are due to faults in the basic design.

There was once a time when a designer could hope to work on over 10 different aircraft during his lifetime and his experience grew rapidly. Today an aircraft can take up to 15 years from feasibility study to becoming fully operational. Unless a design fault shows up during routine testing the aircraft may have been in service for several years before the defect pattern asserts itself. By this time the designer will probably have incorporated the same fault into his next design, although there is a high probability that with today's mobility of labour the original designer will have moved into another field and the new designer will be incorporating his predecessor's mistakes as well as his own. Under the present system there is no incentive for the designer to improve the reliability of his equipment. In fact, the component manufacturer whose products are less reliable than the average makes more money out of his repair contracts than the more conscientious manufacturer as long as the unreliability is not large enough to draw attention to itself.

5.2.1 Reliability Improvement Warranty

In an attempt to improve this situation a recent innovation in U.S.A. has been the Reliability Improvement Warranty. This was originally proposed by Lear Siegler Inc. under the name of Failure Free Warranty. This was rather a bad choice of words, as it did not guarantee that the equipment would not fail, it was not free and it did not imply buyer protection against poor workmanship. What it did guarantee was much better aircraft availability at a fixed price.

Under the warranty conditions, the manufacturer agrees that, over a specified time (which if full advantage is to be gained should extend over several years) he will repair or replace within a specified turn round time all items of his equipment that fail. Any exclusions must be specified in advance. If necessary, the manufacturer can be required to keep sufficient stocks of spare items to guarantee a 24 - hour exchange of a serviceable item for a failed item. In return, the manufacturer is guaranteed a fixed price irrespective of the number of failed items that occur. He is also encouraged to provide no-cost modifications that will improve the design and engineering to enhance the reliability and maintainability of the equipment. The manufacturer is thus provided with a direct monetary incentive to improve the reliability of his product. He is also encouraged to investigate why failures occur and to actively pursue methods of prevention. Every failure he can prevent is reflected directly in his profits.

The contract is also beneficial to the customer. He knows in advance exactly how much his repair bill will be for the item. He can also reduce his stocks of spares to a minimum knowing that there is a guaranteed turn round time that can be as short as 24 hours. His aircraft availability due to this item is entirely dependent on his own logistic ability and will not be influenced by the manufacturer's internal problems. As the manufacturer's no-cost modifications begin to take effect, the reliability of the aircraft will increase. There will also be a reduction in manpower and skill levels required to maintain the equipment and the only test equipment required will be for diagnostic purposes and even this will decline as on-board equipment monitoring systems are introduced.

This approach has many similarities with an "all-risks" insurance policy. The customer pays a fixed premium to ensure maximum aircraft availability. The insurer has the additional advantage of being able to minimise his risks by improving the product reliability and hence maximising his profits.

The Reliability Improvement Warranty is a method for improving the reliability of aircraft that are already built. It would be much more cost effective if the reliability could be improved at the design stage. Unfortunately, Reliability is a function of time and hence cannot be measured when time is zero or negative i.e. before the component is built. However, an impossible task has always been a worthwhile challenge to a good engineer and although evolution has always been a rapid process in the aircraft industry it has mostly been by product improvement rather than by mutation. Consequently, recent history can be a good baseline from which to extrapolate future trends and a study of the main causes of unreliability shows that many areas have shown no improvement for several years and, in fact, that in some areas standards are actually deteriorating. If these trends can be arrested and reversed, there is scope for a large reduction in support costs which will more than offset any consequent increases in acquisition costs.

5.2.2 Reliability Incentives

A major difficulty is to motivate a component manufacturer to do something whose only result as far as he is concerned will be to drastically reduce his lucrative repair contracts. Much thought has gone into devising a system of incentives and penalty clauses that are acceptable to the manufacturer and enforceable by the customer. This type of system is only applicable in a situation where market forces prevail. If a manufacturer has a virtual monopoly he is not interested in incentives and it is impossible to enforce penalty clauses.

Where contractual Reliability is possible it is necessary to draw up a Design Reliability Plan. This requires the manufacturer to perform a Failure Mode and Effect Analysis early in his design and agree with the customer the methods he will use to maximise Reliability. Particular attention is required to be paid to parts or materials that are:-

affected by the harsher aspects of the environment

subject to excessive wear

new or untried in this application

costly to repair

affected adversely by manufacturing or assembly tolerances

It is very important that any failures that occur during development testing should be investigated thoroughly and their likelihood of occurring in service assessed carefully. There is a strong tendency to ignore minor faults that occur on test rigs by saying that the rig is not properly representative of flight conditions and we will wait and see if the fault reappears on flight testing before taking any action. We have already noted that resistance to modifications increases with time and by the time a fault is confirmed in flight, production may have started, by which time resistance is gaining momentum rapidly. Many persistent failures in service can be traced back to faults that were first noted during development testing but ignored.

After one particular type of aircraft had been in service for several years, it was bought by a new customer and immediately complaints were received that during refuelling a sticking float switch would often cause fuel venting. As the float switch design was by now obsolete, it was replaced by a thermistor device and the fault was cured. However, the product support engineer's curiosity was aroused as to why a float switch with no previous fault history should suddenly become troublesome. His investigations soon showed that the device had always had this fault but no one had ever bothered to report it, since it could always be cured by stamping on the aircraft wing at a certain point. He also discovered that there was a note in the original test report to the effect that the switch was prone to sticking, but could be cured by thumping the side of the test tank. In this case a course of inaction was probably justified, but there must exist many other cases where minor faults are producing much frustration and unnecessary cost both in money and downtime, where a little extra effort during the design stages could have prevented the fault from ever occurring.

A Production Reliability test for all components is expensive, but if it can be made sufficiently comprehensive, it will eliminate at source many faults that would otherwise not show up until the aircraft is in service. In particular, it would highlight the defects that occur in infant mortality and those caused by production methods. It is necessary to carry out Qualification Testing on a new component before production starts and hence the test component must be "hand-built". This means that defects caused by production methods (eg casting instead of forging or machining, rolling threads instead of cutting, batch processing,) will not show up.

In cases where it is difficult to motivate a manufacturer to be Reliability - conscious, it is necessary for the customer to maintain a close liaison during the design and development process. Every drawing, test plan and report must be scrutinised from a Reliability view point. Every opportunity must be taken to inaugurate reliability improvements and after testing is complete a Reliability demonstration should be arranged. Suitable corrective action must be taken after all test failures. Only in this way can a consistent programme of reliability growth be assured and the lowest possible support costs encouraged.

Where there is healthy competition amongst manufacturers it is often difficult to decide which manufacturer is offering the most reliable product. In this case it is possible to introduce an incentive/penalty type of bidding. One method is for the customer to specify a minimum Mean Time Between Failures (MTBF). Each manufacturer then proposes any MTBF greater than the minimum and a corresponding Life Cycle Cost. The combination of MTBF and LCC is then assessed for each manufacturer to determine the successful bidder. A penalty clause is then included to guarantee free spares and maintainability if the MTBF is not achieved. The major difficulty with this scheme is the problem of determining the actual MTBF and it may be necessary to prove this by a special laboratory or field test.

An alternative to this method is for the manufacturer to specify maximum and minimum limits for MTBF. If the actual MTBF is less than the target minimum, the manufacturer's profit margin is reduced and

conversely, if the actual MTBF exceeds the maximum, the profit margin is increased. Unfortunately this method also suffers from the difficulty of measuring MTBF when only a few units are available.

5.2.3 Repair Costs

The support costs of each component are greatly influenced by the number of spares required. These in turn are affected by the turn round time of the repair loop. Turn round time is seldom less than 3 months and can be as high as 12 months or more. This means that sufficient spares must be carried to cover up to a year's total defects plus a contingency allowance. The rapid increase in aircraft complexity over the last few years has meant that the cost of spares stocks is now a significant part of the support costs. These are further inflated by the corresponding ancillary costs of paperwork, accounting, auditing, computer memory holding, transport, storage, packaging and stores heating and lighting. These ancillary costs are no longer insignificant and it should be remembered that many of them are incurred again during the repair loop. In many cases, these costs are greater than the manhours' costs of replacing a component and it is necessary to give serious thought at the design stage as to whether a component can be broken down into throwaway modules. This may increase the acquisition costs but the complete elimination of the repair loop can result in a major saving in support costs. This decision of repair v. throwaway must be taken at the design stage as the design philosophy in each case can be quite different. It should be remembered that the skill level required to replace a module at first line is much less than that required to repair it at second line.

5.2.4 Unforeseen Support Costs

Assuming that a decision has been made that an item is to be regarded as repairable there are many areas where support costs can be greater than anticipated. The following examples illustrate this point.

Wrong Diagnosis This originates from low skill levels or the use of wrong or inaccurate test equipment. This can escalate costs also if a piece of "good" equipment is put into the repair loop with its attendant ancillary costs and loss of availability. Excessive diagnostic time also originates from similar causes. Both can be eliminated by built in test equipment and on-board health monitoring that will pin point the fault automatically.

Failure to Allow For Permissible Component Degradation Most components degrade over the life of the aircraft and allowance for this is made in the specification. Test equipment must be calibrated so that only components below the degraded level are failed. If it is set to the level for new equipment many components will fail the test and be put into the repair loop whilst still serviceable.

Careless Handling This seems to be increasing. It can account for one defect in every ten. Since these defects are, in theory, all avoidable, better design and better operator education could show a marked reduction in support costs.

Wrong Packaging and Labelling This is allied to the previous example and is also avoidable but is unfortunately becoming more prevalent. It can cause considerable waste of time and loss of availability with a consequent increase in support costs. An item in the wrong stores is effectively "lost" since it cannot be "retrieved" by the computer.

Poor Quality Control This is another area that, in theory, can be eliminated by careful inspection, but in practice, it accounts for one third of all faults in new equipment. If spare components are not tested before fitting to an aircraft there is a one in three chance that the aircraft will still be unserviceable after the "repair". This is an important area that is often forgotten in calculating support costs and can be an important part of loss of availability of aircraft.

5.2.5 Examples of Items with Unnecessarily High Support Costs

The following examples of high support cost items are regarded as typical of those encountered in mechanical systems during the last ten years. Most of the defects could have been avoided if more care had been taken during the design, manufacture and operation of the components.

5.2.5.1 Fuel Tank Float Switches

These are magnetically operated reed switches actuated by permanent magnets in rising or falling floats. They are used to operate a warning lamp, a magnetic indicator or a relay which in turn opens or closes fuel valves.

5.2.5.1.1 Quality Control

Quality control was generally found to be poor over a wide spectrum of components and manufacturers and appears to be a reflection of a general lowering of standards. Usually, the aircraft itself is not affected as the fault is found before the component is installed and the item is diverted into the repair loop, but this results in an unnecessary increase in support costs. In the case of the float switch, 24% failed the airframe manufacture's acceptance test, resulting in unexpectedly high ancillary costs caused by extra paperwork, transport, accounting, inspection, progress and programming alterations. The length of time in the repair loop also resulted in shortages occurring during aircraft build.

5.2.5.1.2 High Electrical Load

This resulted in burnt, sticking and welded switch contacts and was traced back to poor liaison at the design stage between switch manufacturer and airframe manufacturer. This accounted for 10% of all defects on one type of aircraft. The initial specification did not supply sufficient details of the electrical currents and associated components (although to be fair many of them were not actually defined at

that stage) and the suppliers literature lacked full details of the switches' limitations. Similarly the qualification testing did not include all the other components in the electrical circuit.

5.2.5.1.3 Rough Handling

This type of defect is caused mainly during transit and installation. In this case it accounted for 11% of defects and means that one defect in every ten was theoretically avoidable. Improved packaging and the liberal use of polystyrene foam should have reduced this type of defect but this seems to have been offset by an increase in handling breakages before and after packaging. This particular switch appears at first glance to be a relatively robust piece of equipment and there is no indication that it contains delicate glass reed switches. There is a need for operator education to impress on everyone concerned that all aircraft equipment should be handled with care.

5.2.5.1.4 Installation and Fitting Problems

Aircraft fuel tanks are not normally the most accessible components. If accessibility is poor then there is a high probability that a component as fragile as a float switch will be damaged during build or in-service replacement. It is impossible to make every component on an aircraft equally accessible but designers seem more concerned about fitting a component into the space allocated for it on the drawing than in how this is to be achieved in practice.

In one particular tank, the high level switch had an apparent failure rate many times higher than the switches in adjacent tanks and yet when removed from the tank it usually proved to be fully serviceable and the fault could not be reproduced. Because in this case the designer had made it particularly accessible by mounting it adjacent to the filler cap the fault was tolerated for many years until one particularly astute engineer discovered that the float could be fouled by the filler cap retaining wire. Moving the wire attachment point to the other side of the opening solved the problem.

5.2.5.1.5 Contamination by Fuel

Because the internal circuit boards were ostensibly sealed against fuel ingress, no attention was paid to using fuel-proof materials. A higher than normal failure rate for the seals led to consequent failures of the circuit board components. Coating the finished circuit boards with fuel-proof varnish would have prevented these failures which amounted to 6% of all defects.

5.2.5.2 Fuel Transfer Pump

This fuel pump, used to transfer fuel between aircraft fuel tanks, consists of an impeller driven by a 3 - phase A.C. flooded motor. It contains three thermal fuses buried in the motor windings to prevent overheating in "run-dry" or 2 - phase supply conditions.

5.2.5.2.1 Quality Control

As in the previous case faults due to poor quality control were extremely high (3[illegible]% of all defects). This incidence is worrying as this type of support cost is not usually allowed for in Life Cycle Costing.

5.2.5.2.2 Thermal Fuse Operation

The thermal fuses were not renewable except by rewinding the motor. This was not considered to be a problem at the design stage as a historical survey of similar motors showed that the probability of overheating was very small and the fuses were only included to prevent a possible fire hazard.

On one particular aircraft, however, unforeseen problems occurred with the electrical plug and socket. There was a lack of liaison between the pump manufacturer and the airframe manufacturer with the result that the mating pins were made of incompatible materials and severe electrolytic corrosion occurred. Added to this, the electrical pins in the plug were insufficiently protected against rough handling and many cases of bent or broken pins occurred. The net result was loss of one phase and 20% of the defects of this pump were caused by "blown" thermal fuses with consequent scrapping of the motor windings. This again caused high support costs and shortage of spares.

5.2.5.3 Scratched Transparencies

It was noticed on a certain fighter aircraft that the port windscreen transparency was being replaced because of both internal and external scratches twice as often as the starboard one. An investigation showed that the external surface was being scratched by the pilot's personal equipment connector as he entered the cockpit and that the coaming on the inside formed a convenient shelf on which to rest a tool box when working inside the cockpit. Hence, the support costs for the port transparency were twice those of the starboard one.

5.2.5.4 Hydraulic Oil Filter

Whilst inflation affects both material and labour costs it is important to recognise that they do not necessarily increase at the same rate. When a hydraulic system was being designed 15 years ago a decision was required on whether to use a disposable or cleanable hydraulic oil filter element. The cost of cleaning an element then was half the cost of a disposable one, so the cleanable one was chosen. Today, the cost of cleaning the element is 150% of the cost of a disposable one. Another unexpected finding was that 50% of all elements removed are found to have broken or distorted elements which necessitates replacement at twice the cleaning cost.

5.2.5.5 Hydraulic Pump

This illustrates the difficulty of forecasting support costs of new, untried equipment. Several years ago a new type of pump appeared on the market. For a given performance, this pump offered attractive savings in cost and weight and the predicted reliability was equal to that of existing pumps. Its first application to a commercial aircraft was very successful and on this record it was selected in an uprated version for a military aircraft. Initial qualification tests were very successful but the first production pumps suffered from a high infant mortality rate. The manufacturer blamed his subcontractors and tightened his specifications and inspection procedures. This had very little effect and several modifications were proposed and accepted. After two years in service the infant mortality rate had been halved but the overall MTBF was only 500 flying hours. After three years this had increased to 600 hours but one year later it had reduced to 300 hours. At this point the predicted Life Cycle Costs over the next ten years were re-calculated and compared with the costs of completely re-equipping the fleet with an older conventional pump. Completely re-equipping the fleet showed an estimated saving of $ 3M including initial cost, repair costs and support for the original pump over the phase - out period, so the changeover was authorised. When the ten years are up it will be interesting to see how accurate the revised Life Cycle Cost has been.

5.2.5.6 Air Pressure Regulating Valve

This valve was used to control the pressure of hot air fed into the air conditioning system from the engines. During the first production run a batch of castings happened to be porous. The foundry later claimed that they could not have discovered this without extensive inspection which they did not consider to be necessary. After machining, the porosity was obvious to the naked eye and an unsuccessful attempt was made to seal the valves. They were completed and sent to the airframe manufacturer where they were rejected causing an acute shortage of units on early build aircraft. This is really a failure of the financial system. Where a subcontractor is paid on delivery, irrespective of whether the unit is subsequently rejected, there can be no incentive to provide meticulous inspection, even if a warranty is involved, as cash-flow becomes an over-riding factor. This is compounded in many cases where a rejected item enters the repair loop under a completely different accounting system. However, from the aircraft purchaser's point of view there is no way in which this can be described as a cost effective system.

5.2.6 Human Factors

These few examples (mostly taken from Ref. 1) show that predicted values of reliability based on random failures do not allow for the human factors involved in the majority of defects. A survey of over 4000 defects in aircraft mechanical systems revealed that most defects were related to the internal operating conditions of the component (contamination, vibration, temperature, etc.) or to poor quality control during manufacture. Very few were related to the external environment conditions of the aircraft. This is illustrated by the following table.

	DEFECT CLASSIFICATION					
	External Environment Conditions	Internal Operating Conditions	Handling	Quality Control	No Fault Found	Not Known
Fuel	3%	26%	13%	30%	20%	8%
Hydraulics	0%	46%	6%	26%	12%	12%
Air. Cond.	6%	7%	9%	62%	14%	2%
Overall	2%	33%	9%	31%	16%	9%

This confirms that if we wish to reduce our support costs we should concentrate our efforts on improving quality control at source, better operator education and making the design teams more reliability conscious.

6. CONCLUSIONS

Life Cycle Costs comprise acquisition costs, operational costs and support costs and their successful forecasting requires extrapolation from an accurate data base. However, aircraft technology advances rapidly and the components of the data base are not stable. The extrapolation requires considerable insight and expertise if it is to provide an accurate interpretation of future costs.

Life Cycle Costing is too involved a subject to be solved by conventional accounting techniques which depend on the extrapolation of historical data. It encompasses a breadth of experience that involves many different disciplines, not least of which is the basic engineering of the aircraft. Although based on scientific principles, engineering also requires a certain amount of intuition which can only be acquired through practical experience.

Accountants always seem slightly puzzled as to why everything always costs a little more than they have estimated, no matter how many contingency allowances are included in their estimates. I hope this paper will have contributed a little towards their enlightenment.

7. REFERENCES

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8. ACKNOWLEDGEMENT

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BALANCED DESIGN - MINIMUM COST SOLUTION

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ABSTRACT

Today's weapon system designers are faced with the challenge as well as the requirement to balance performance, schedule and life cycle cost (LCC) during the design and development of any new weapon system. This paper discusses the application of the life-cycle cost analysis, the significant design and manufacturing cost drivers, and the techniques used to assess LCC during the different phases of weapon system development. The paper also presents an illustrative case study showing the benefits of the application of life-cycle costing on availability, sustained sorties, and support requirements.

I. INTRODUCTION

Inflation and budget restrictions during the past several years have reduced the availability of funds for the procurement and operations of weapon systems. Consequently, tradeoffs among performance, schedule and life cycle cost (LCC) have become a much more important part of the evolution of the weapon system design. This paper discusses the Balanced Design approach in which LCC analysis is used during the evolution of a weapon system to assist in the balance of performance, schedule, and cost. The paper also identifies the major cost drivers and techniques used to establish life cycle cost. For this paper, the term LCC is used to denote the cost for development, procurement and peacetime operations of a weapon system. A typical fighter aircraft LCC includes development cost (10%), procurement cost (35%), and 15 year operations and support (O&S) cost (55%). The major cost categories and elements of LCC are:

Development Cost. Includes the cost of design and development, test and evaluation, flight test support (e.g., ground support equipment (GSE), spares, and personnel), and data (e.g., test reports, stress reports) for the new aircraft system. Approximately 90 percent of this cost category is attributed to the design, manufacturing, and testing activities of the new aircraft system. The cost of the development activity is driven by the mission capabilities (air-to-air vs. air to air and air-to-ground), physical characteristics (size, weight, etc.), and R&M (reliability and maintainability) characteristics (MTBF, MTTR, etc.) of the new aircraft design.

Procurement Cost. Includes the flyaway cost (airframe, engine(s), and avionics), initial support (GSE, spares, training and training equipment, and inventory entry and management), system project management, test and evaluation, data (e.g., technical publications, training manuals) and facilities for the new aircraft system. Approximately 95% of this category is attributed to flyaway, GSE, and initial spares cost. Procurement cost is driven by mission capabilities, R&M characteristics, number of bases, maintenance concept and training system requirements.

Operations and Support Cost. Includes the cost elements of personnel, replenishment spares, depot maintenance, base maintenance material, fuel, item management, replacement training, modifications, and facilities. Approximately 85 percent of the cost of this element is attributed to personnel requirements, replenishment spares, depot maintenance, base maintenance material and fuel of the new aircraft system. The O&S costs are driven by the maintenance concept, MFHBF (mean flight hours between failure), unit equipment cost, overhaul intervals, fuel consumption rate, force size, and utilization rate.

II. APPLICATION OF LIFE CYCLE COST ANALYSIS

The tradeoffs among performance, schedule and cost involve many complex and related parameters (e.g., range, payload, materials, production rate, weight, reliability and maintainability). LCC is used to quantify these parameters and establish a figure of merit for selecting among alternative concepts, configurations and design. The pricipal application areas for LCC analysis are: (1) design and analysis, (2) source selection, (3) program management, and (4) support resources planning.

Design and Ananlysis

In the design and analysis of a new weapon system, LCC can be used to support trade studies, equipment selections, and configuration refinements. During the design and analysis process, most relevant design parameters (e.g., weight, materials, R&M, etc.) can be reduced/related to cost estimates and can be used as decision parameters. This process provides the designers a full knowledge and understanding of the cost benefit/penalty of the design decisions. Figure 1 presents the "Design to Life Cycle Cost" (DTLCC) process that can be employed to develop the LCC estimates used in the design decision making process.

The DTLCC process provides the designers and program managers a systematic approach of assessing the relevant design parameters. The greatest opportunity to reduce LCC and improve performance is during the conceptual/prototype phase and the initial months of Full Scale Development (FSD). The funds expended during this time period are rather small in comparison with the total system LCC. Nevertheless, the design decisions made during this period have profound cost implications on the procurement and operations and support cost. Many cost benefits can be derived by a concerted effort to apply LCC early in the system development phase.

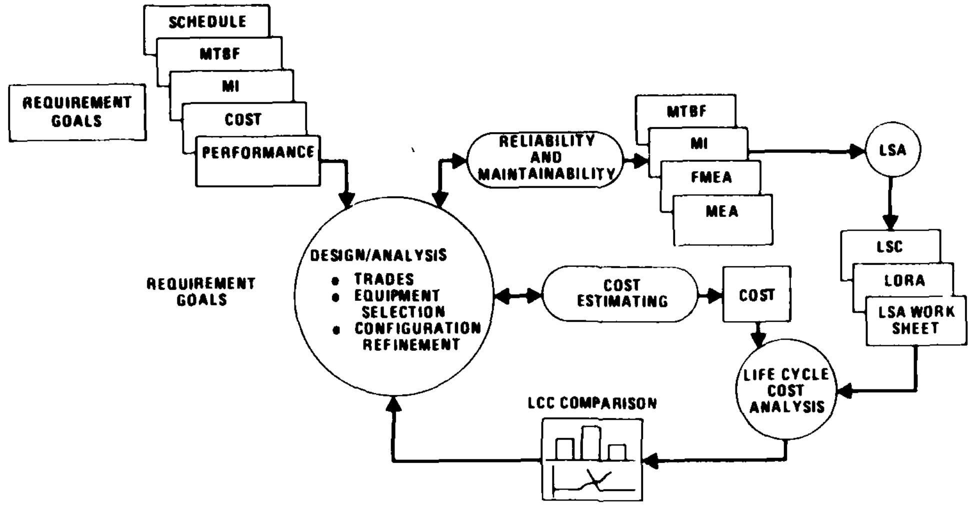


FIGURE 1. DESIGN TO LIFE CYCLE COST PROCESS

Source Selection

A significant part of the aircraft LCC is driven by the equipment selected from suppliers. A large portion of an aircraft's failure rate and maintenance requirements is directly affected by the selected equipment. The ability to impose and control the equipment of the suppliers plays an important role in the achievement of the aircraft LCC objectives/goals. The first step is to incorporate LCC requirements into the procurement specifications. In the establishment of the procurement specifications, LCC sensitivity analysis can be performed to arrive at a set of equipment parameters which will provide a balanced solution of performance, cost and schedule for that equipment. The desired parameters (e.g., reliability, maintainability, etc.) are incorporated in the procurement specifications and become contractual requirements imposed on the suppliers.

Once the balanced procurement specification for the equipment has been established, the next step is to select the supplier which can meet the specification. LCC analysis is used to assess each supplier's proposal/submittals. LCC analysis is also used to assess the cost implications of different design parameters among alternative submittals. Because suppliers' proposals may exceed or fall short of the specification requirements, the evaluation of the proposals must be put on a comparable basis. If not, the evaluation might be based on erroneous information, resulting in the selection of the wrong supplier. For example, three suppliers of a piece of equipment provided the data shown in Figure 2. If the evaluation was based solely on the submitted proposal, supplier A LCC would appear lower than that of the other suppliers. In order to have a better

SUPPLIERS	A	B	C
DEVELOPMENT	1.00	1.20	1.50
PROCURMENT	1.00	1.20	1.30
O&S	1.00	0.95	0.90
LCC	1.00	1.06	1.10

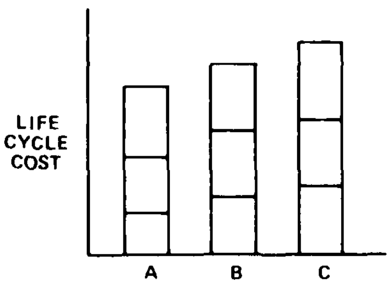


FIGURE 2. INITIAL LCC ANALYSIS

understanding of the suppliers' proposals, the three suppliers were asked to provide their development costs and unit procurement costs sensitivity to variations in design parameters. Figure 3a presents part of the suppliers' response. The 0 points represent the suppliers' initial submittal. Supplier C equipment was designed to a much higher MTBF than either supplier A or B and with a correspondingly higher development and procurement cost. Using the same MTBF for each supplier resulted in a reversal of LCC rank order, as shown in Figure 3b. Consequently, supplier C was selected.

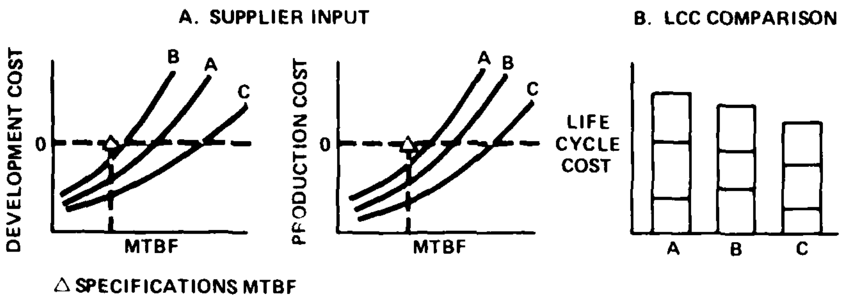


FIGURE 3. LCC ANALYSIS

To ensure that the procured equipment can and will meet the procurement specifications, tracking and monitoring of the selected supplier's progress is a requirement. LCC analysis can be extremely useful in this task. Based on the procurement specifications, LCC analysis can establish the equipment LCC baseline. Subsequent changes to the equipment parameters (e.g., reliability, maintainability, unit cost, etc.) can be evaluated to determine the impact on the baseline LCC, and deviations from the LCC baseline can be monitored. If the equipment LCC estimate is exceeding the baseline, corrective actions can be imposed on the supplier.

Program Management

Today, LCC and O&S cost objectives are being imposed as part of the contractual requirements to make cost equal in importance with performance and schedule. A program manager now must pay as much attention to O&S cost as to acquisition cost, performance and schedule. In order to meet the contractual LCC objectives, the program manager must quantify LCC drivers and the influence of design on cost. With the quantification of the LCC drivers, the program manager can establish "design-to" objectives (e.g., unit cost, reliability, maintainability, weight, etc.) for each of the major subsystems and assign these objectives to the subsystem design managers. These objectives are used by the design managers in the design of their subsystems. This gives the individual subsystem manager and designer the responsibility of achieving contractual LCC objectives.

As the design evolves, LCC analysis can be used to track and monitor the design changes and their effect on aircraft LCC. LCC analysis provides the program manager visibility of the LCC program. If the evolving design LCC estimates exceed the LCC target, the manager can initiate actions and coordinate trade-offs among different subsystems.

Support Resources Planning

LCC analysis is used to evaluate the alternative support resource requirements. The objective of support resources planning is to develop support plans that will provide the needed resources to achieve the operational requirements (e.g., operational ready (OR) rate, sortie capabilities) of the new system. During the system design process, extensive analysis should be performed to assess the support requirements and resources needed for the new aircraft system. A great deal of the O&S cost is driven by the evolving design, but there are other significant O&S cost drivers which must be assessed. These contributors can include such requirements as the maintenance policy, training and training equipment, GSE, deployment concepts, and utilization.

III. COST DRIVERS

The design of the aircraft has an impact on all cost elements of the aircraft LCC. The aircraft design is driven by the user's performance, specifications, and the O&S objectives. The performance requirements for an aircraft are generally expressed as range, payload, speed, altitude and mission roles (air-to-air only vs. air-to-air and air-to-ground). The specification requirements include material, corrosion control and fatigue life. The O&S objectives cover the MTBF, MTTR, deployment concept and utilization rates.

The requirements shown in Figure 4a are examples of factors that influence the evolving design. The following example is presented to illustrate this point. The example addresses one aspect of the process of establishing the criteria for the selection of the engine. Engine characteristics that influence aircraft LCC include engine thrust-to-weight ratio, specific fuel consumption, length, diameter, and airflow. For subsonic to Mach 2 class aircraft, the cost drivers are engine thrust-to-weight (T/W) and mission average specific fuel consumption (MASFC). Improvements in T/W or MASFC result in a smaller aircraft to perform the same mission, and conversely a smaller aircraft will have a lower LCC, all other things being equal. For this example, the aircraft mission capability was held constant. The values of T/W, MASFC and LCC are normalized to 1.0. The range of variation in T/W and MASFC is ±25 percent. Figure 4b shows the sensitivity of the LCC to variations in T/W and MASFC.

A. TYPICAL DESIGN COST DRIVERS

- PERFORMANCE REQUIREMENTS
  - RANGE
  - PAYLOADS
  - SPEED
  - MISSION ROLES
- SPECIFICATIONS
  - CORROSION CONTROL
  - FATIGUE LIFE
- R&M REQUIREMENTS
  - MTBF
  - MTTR

B. RESULTS OF LCC ANALYSIS

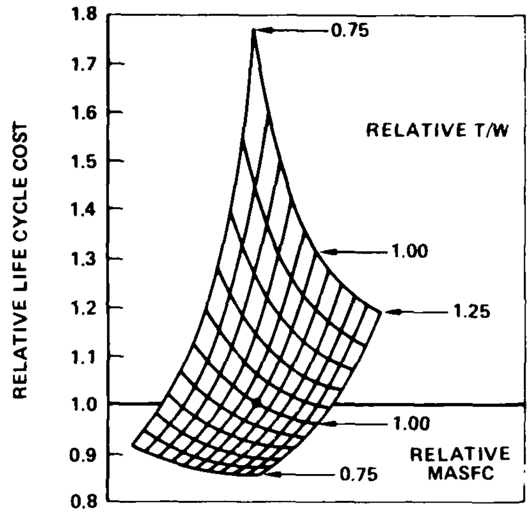


FIGURE 4. EFFECT OF DESIGN COST DRIVERS ON LCC

Performance, specification, and O&S requirements drive the design (e.g., size, configuration, weight), and influence manufacturing cost. Material selection can be driven by the weight objective of the aircraft system. In order to meet a specified weight objective of the aircraft, extensive usage of titanium in lieu of aluminum might be required, which has a definite impact on the manufacturing cost. Figure 5a shows some of the manufacturing cost drivers, and Figure 5b presents an example of the cost implication of changes in manufacturing process.

An LCC analysis was performed to assess the cost impact of manufacturing components either by machining or forging. The finished part under investigation is the same for both processes. The analysis shows that the initial cost for the machined parts is minimal, whereas the initial cost for the forging is rather large, but the recurring cost for the forged part is lower. From the analysis, a solution for designing the part is based on the total program LCC relative to the number of units produced.

A. TYPICAL MANUFACTURING COST DRIVERS

MATERIAL
- TITANIUM
- ALUMINUM
- COMPOSITE
- STEEL

STRUCTURE
WING
- WET VS. DRY
- NUMBER OF HARD POINTS
- COMPLEXITY OF CONTROL SURFACES

BODY
- WING ATTACHMENT
- LANDING GEAR ATTACHMENT
- NUMBER OF SUBSYSTEMS
- NUMBER OF OPENINGS

MANUFACTURING PROCESS
- SHEET METAL
- MACHINED PARTS
- FORGINGS
- CASTINGS
- BONDING

SUBSYSTEMS
FLIGHT CONTROL
- MECHANICAL VS. FLY-BY-WIRE
- NUMBER OF REDUNDANCIES

LANDING GEAR
- LAND VS. CARRIER BASED
- NUMBER OF WHEELS & BRAKES

B. RESULTS OF LCC ANALYSIS

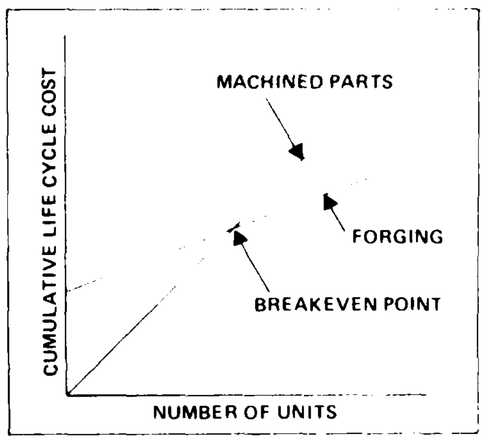


FIGURE 5. EFFECT OF MANUFACTURING COST DRIVERS ON LCC

Figure 6a presents typical O&S cost drivers of an aircraft system. The principal O&S parameters, namely, MTBF, remove-and-replace time, base-versus-depot repair, MTTR, and unit spares costs, are determined by the design configuration and equipment selection. For example, the quantity of spares required and the maintenance frequency of the equipment is influenced by the equipment MTBFs and MTTRs. Fuel cost is driven by the fuel consumption, aircraft configuration, engine characteristics and mission durations. The sensitivity of LCC to variations in aircraft MTBF are presented in Figure 6b. The figure shows the influence of improvements of reliability on cost. That is, an improvement in system MTBF decreases the relative O&S cost. However, the savings in O&S cost are diminished by the higher acquisition cost required to achieve the MTBF objectives.

A. TYPICAL O&S COST DRIVERS

- UNIT SPARES COST
- FUEL
- MTBF
- MTTR
- PERSONNEL
- MAINTENANCE CONCEPT
- UTILIZATION RATE

B. RESULTS OF SENSITIVITY ANALYSIS

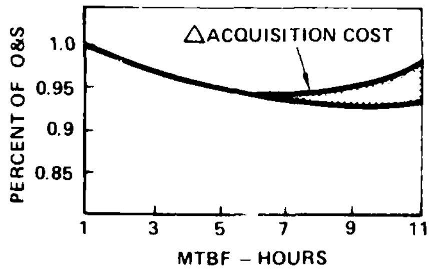


FIGURE 6. EFFECT OF O&S COST DRIVERS ON LCC

IV. LCC ESTIMATING METHODOLOGIES

In order to provide timely and appropriate LCC estimates and comparisons of competing designs, LCC estimating methodology must be tailored to the information available. The techniques can be classified into total system parametrics, subsystem parametrics, and detailed analysis. Figure 7 presents various types of cost estimating relationships (CERs) by program phase, the possible usage for each type, and the accuracies that can be expected.

TYPE	EXPECTED ACCURACY
• TOTAL SYSTEM PARAMETRICS (CONCEPTUAL/PROTOTYPE/FSD)	±30%
– WEIGHT – SFC – SPEED – NUMBER OF ENGINES – THRUST	
• SUBSYSTEM PARAMETRICS (PROTOTYPE/FSD)	±15% - 25%
– ELECTRONIC EQUIPMENT MODELS – MISSILE MODELS – AIRFRAME & BASIC STRUCTURES MODELS	
• DETAILED ANALYSIS (FSD/PRODUCTION)	±10%
– DETAIL ESTIMATING – TASK TIME ANALYSIS – ANALOGY – SUPPLIER QUOTES – SCALING	

FIGURE 7. LCC ESTIMATING METHODOLOGIES

Total System Parametrics

Because of limited hardware definition during the early stages of a program, parametric cost estimating is used to estimate total program cost. Parametric cost estimating uses mathematical relationships derived from historical cost data. Total system parametric CERs offer obvious advantages because the LCC estimates can be generated with minimum amount of imputs required. Such CERs are used to assess top-level total system cost. A typical example is shown in the following linear relationship.

$$\text{Air Vehicle Cost} = A + B \cdot (\text{Weight}) + C \cdot (\text{Thrust}) + D \cdot (\text{Speed}),$$

where A = fixed cost constant.

B,C,D = parameter coefficients

This type of CER is acceptable for use in the analysis of generic weapon systems for long range planning. The main disadvantages are its insensitivity to the impact of subelement and design alternatives and inherent inaccuracies in not being able to adjust the historical data to a common base. The difficulty of adjusting historical data to a common base can be attributed to (1) variation in the economy, technology and manufacturing technique, (2) differences in production buildup and production rate, and (3) inconsistency in the company's categorization of costs. With the aforementioned adjustment difficulties, the expected accuracy of the total system parametrics is ±30 percent.

Subsystem Parametrics

Subsystem parametrics cost methodology provides the capability to perform trade studies and establish a level of cost that reflect the design, manufacturing and O&S cost drivers. The CERs can be developed using today's cost for the acquisition and support of comparable systems. The CERs of the subsystem require a greater amount of technical input, and the expected accuracy correspondingly improves to ± 15% to 25%. The advantage of the subsystem parametric method compared with the total system parametric method is the improved ability to perform subsystem trade studies. Figure 8 provides examples of appropriate subsystem parameters.

ELECTRONIC EQUIPMENT	MISSILES	AIRFRAMES & BASIC STRUCTURES
• WEIGHT	• SEEKER WEIGHT	• COMPONENT NUMBER & WEIGHTS
• VOLUME	• SEEKER TYPE	• WETTED SURFACE
• DESIGN COMPLEXITY	• FUZE WEIGHT	• DESIGN GEOMETRY
• MANUFACTURING COMPLEXITY	• FUZE TYPE	• DESIGN LOADS/DYNAMIC PRESSURE
• DISSIPATED POWER	• MOTOR WEIGHT	• FUEL INERTIA
• AMOUNT OF NEW DESIGN	• MISSILE DRAG	• DAMAGE/REPAIR SUSCEPTIBILITY
• INTEGRATION EFFORT	• MISSILE WEIGHT	

FIGURE 8. SUBSYSTEM PARAMETERS

Detailed Analysis

The cost estimating methodology based on detailed analysis is employed where there is sufficient definition of the system/subsystem under consideration. The basic methods and approach should be tailored to the level of the detail hardware descriptions. The methods used include: (1) detailed cost estimates involving the application of industrial engineering standard hours and the assessment of manloading requirements; (2) analogs that relate costs of existing hardware to new hardware; (3) subcontractor and supplier quotes; and (4) scaling/parametric CERs for components.

During the detailed analysis, specific attention should be placed on both the design and programmatic cost drivers, such as the impacts of material application, subsystem design, test requirements, reliability and maintainability, production gaps, rate buildup, improvement curves, funding requirements, and long-lead requirements. Figure 9 presents the detail components used in LCC analysis relationships. The accuracy of this method improves to ± 10%.

LCC COST ELEMENTS	PARAMETERS	TECHNIQUES
• UNIT PROCUREMENT	• MANUFACTURING TECHNOLOGY	• DETAIL ESTIMATING
• SPARES	• MTBF	• TASK TIME ANALYSIS
• BASE MAINTENANCE	• MTTR	• ANALOGY
• DEPOT MAINTENANCE	• CONDEMNATION RATES	• SUPPLIER QUOTES
• FUEL	• REPAIR TIMES	• MAINTENANCE ENGINEERING ANALYSIS
• SUPPORT EQUIPMENT	• BASE/DEPOT REPAIR	• DEPOT STANDARDS
• FACILITIES	• UNIT SPARES COST	• STATISTICAL ANALYSIS
• DATA	• DESIGN LIFE	• SCALING

FIGURE 9. DETAIL COMPONENTS USED IN LCC ANALYSIS

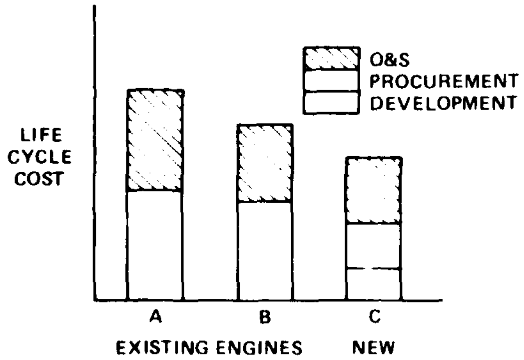
V. CASE EXAMPLES

The following examples are presented to illustrate how LCC analysis is used during the development and evaluation of a weapon system. The examples given touch upon the different applications areas of LCC.

Design and Analysis

The opportunity to improve performance and/or reduce life cycle cost is the greatest during the early phases of design and analysis. The following example illustrates how LCC analysis was employed in the selection of the engine for a new aircraft. During the conceptual phase, the aircraft designers assessed the user's requirements and determined the desired engine characteristics (e.g., thrust to weight, specific fuel consumption rate, etc.). Based on the preliminary assessment, LCC estimates were developed for existing engines and new engines with the desired engine characteristics. The results of the LCC assessments are presented in Figure 10a. From the analysis, significant cost differences were obtained between the existing engines versus the new engine. The decision was made to use the new engine for the aircraft under development. The reasons for the cost differences are summarized in Figure 10b.

A. ENGINE LCC COMPARISON



B. ENGINE LCC IMPROVEMENT

	NEW (C)	OLD (B)
• PART COUNT	15,000	20,000
• MEAN FLIGHT HRS BETWEEN FAILURE (MTBF)	250 HR	150 HR
• BASE REPAIR RATE	90%	60%
• BASE DIRECT MANHOURS/FLIGHT HOUR	1.0	2.0
• DEPOT MANHOURS/OVERHAUL	1,000	2,000
• PERCENT INITIAL SPARES COST	17%	25%
• ENGINE UNIT COST	$550K	$600K

NEW ENGINE DESIGN LCC COST 30% LOWER THAN OLD DESIGN

FIGURE 10. ENGINE SELECTION LCC ANALYSIS

Equipment Selection

Applications of the Design-to-LCC concept to the equipment selection also have high payoffs. The following example illustrates the benefit that can be obtained by using the DTLCC concept to aid in the design of a subsystem. The example addresses an LCC assessment to determine the Auxiliary Power Unit (APU) design-related MTBF that provides the lowest cost solution. Life cycle cost assessments were performed for APU MTBFs of 800, 1000, and 1200 hours. The results shown in Figure 11 are as expected. Acquisition cost increases with an increase in reliability (MTBF) requirement, at a relatively constant rate within a certain range of MTBFs. Beyond this, the rate of change in acquisition cost increases dramatically, most likely because of costly design changes necessary to meet the higher reliability requirements.

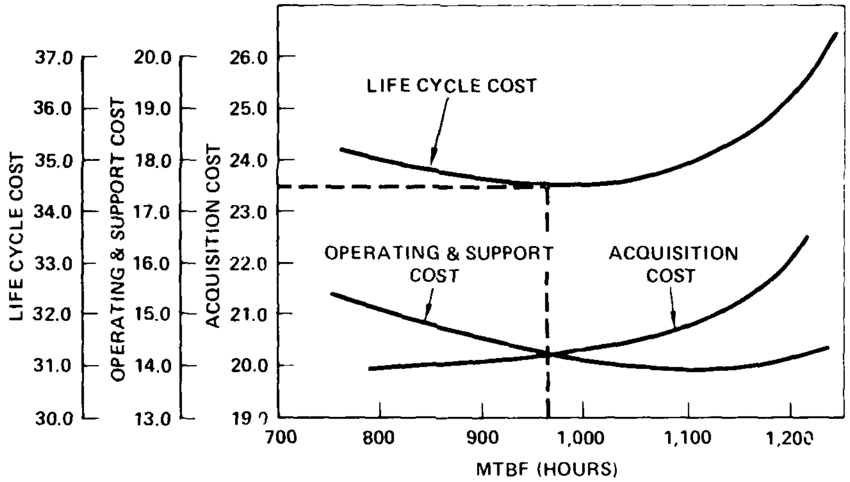


FIGURE 11. MTBF VS. COST AUXILIARY POWER UNIT (APU)

Figure 11 also shows that the associated O&S cost generally decreases with increasing MTBF. However, the extreme end of the O&S cost curve reverses and starts to increase rather than continue to decrease as might be expected. At higher MTBFs, the spares and maintenance requirements are not decreasing enough to offset the higher unit cost for the spares. The selected MTBF at 950 hours for the APU appears to be the lowest cost solution.

Support Planning

Design-to-LCC was used to evaluate the cost implications/benefits of Maintenance Condition Reporting Systems (MCRS). The example shown in Figure 12 summarizes a study that was performed to evaluate the O&S costs for a fighter aircraft equipped with and without MCRS. MCRS provides in-flight monitoring of primary aircraft systems, improved flight line fault isolation and malfunction analysis. These factors result in resource savings of spare, personnel, fuel, etc. The assessment was based on a flying program of 4000 flight hours per aircraft.

	WITHOUT MCRS	WITH MCRS
DEVELOPMENT	--	5
PROCUREMENT	–	45
OPERATIONS & SUPPORT	380	170
Δ LCC	380	220
Δ LCC ADVANTAGE		160

FIGURE 12. Δ AIRCRAFT LCC (MILLIONS $)

Additional benefits can be derived from the incorporation of the MCRS equipment, but they were not quantified in the given example. For example, the MCRS increases aircraft operational ready rate by the extension of the engine periodic inspection interval, reduction in troubleshooting time, trim requirements and functional check flights.

VI. SUMMARY

The LCC is one of the figures of merit that aid in the evaluation of the alternatives during the decision-making process. Balanced Design as a possible minimum cost solution of a new or modified weapon system can only be achieved by the willingness and determination of the users, designers and Program Managers to trade between performance, schedule and cost. The requirement to achieve a "Balanced Design" and the use of LCC to establish "Target LCC's" in the early phase of the program must be used as a control throughout the acquisition phase of the program. Program managers and designers must remember that the lowest acquisition cost solution for any one phase of the program is generally not the minimum LCC solution for the program.

VII. GLOSSARY

APU	Auxiliary Power Unit
BIT	Built-In-Test
DTLCC	Design to Life Cycle Cost
FMEA	Failure Mode and Effect Analysis
FSD	Full-Scale Development
GSE	Ground Support Equipment
I.E.	Industrial Engineering
LCC	Life Cycle Cost
LORA	Level of Repair Analysis
LSA	Logistics Support Analysis
LSC	Logistics Support Cost
M	Maintainability
MEA	Maintenance Engineering Analysis
MFHBF	Mean Flight Hours Between Failures
MI	Maintenance Index
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
O&S	Operations & Support
R	Reliability
R&D	Research and Development
R&M	Reliability and Maintainability

DESIGN TO COST AND SYSTEMS' LCC

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1. Introduction

Design to Cost is a very popular and descriptive phrase which in my opinion can lead to an over-simplification of the problems and objectives which lie behind it. Perhaps splitting up the Design-to-Cost-task into at least three major sub-tasks with their interdependencies and implications leads to a clearer understanding of some of our present difficulties and approaches (Figure 1).

Aside from the tasks of the military planner to which one could apply the descriptive labels

Define to Costs and

Organize to Costs

the Design-to-Cost-task could be differentiated into

Design to Financial Feasibility

Design to Personnel Feasibility

Design to Systems' LCC.

I would like to elaborate on these different aspects of the Design-to-Cost approach with special attention to their Operational and Maintenance Cost and methodological implications.

2. Design to Financial Feasibility

In practical application of the Design-to-Cost approach one surprisingly often encounters the philosophy, that Design to Cost only implies conceiving and developing a weapon system in such a manner as to make it financially feasible within the budgetary restraints. Such Design to Financial Feasibility activities, as I would like to call them, however, are only one aspect of designing to cost. Their sole purpose is to keep increases in budgetary spending within the imposed limitations.

For many years the standpoint of armament and procurement agencies and therefore of industry has been that major effort must be directed to the task of designing and producing a weapon system in such a manner as to generate maximum effectiveness while keeping the project financially feasible. Financial feasibility, however, in practice solely is concerned with financial restraints imposed with respect to Research, Development, and Procurement Costs, that is with keeping these cost categories within the limitations of the investive chapters and titles of the budget. The necessity of keeping the procurement of a desired weapon system within the constraints of these budgetary limitations is usually the combined concern of the procurement agency and the military service requiring the weapon system. Therefore pressure on industry to design a financially feasible system is great; industry concentrates its efforts on reducing Research and Development Costs and the price of the weapon system. This pressure on prices has an increasing tendency due to the fact that the ability of most nations to stay within procurement budget restraints by reducing the number of weapon systems procured is practically exhausted. Further reductions in quantity would induce dangerous degradations of combat effectiveness.

Thus the planner in defining to investment costs and industry in designing to financial feasibility within the investment cost limitations are actually turning back the positive trend of the last years to Life Cycle Cost thinking and Life Cycle Cost oriented designing back to the old, narrow-minded concentration on development and production. The effects on Operation and Maintenance Costs, usually not being explicit financial restraints, are occasionally gratefully ignored or left to later decisions. The fact that Maintenance Costs per Flying Hour in moving from an old generation of fighter bombers to a new generation increases by 34 % without inflation and without military personnel costs seems to illustrate the consequence.

Another negative aspect which is enhanced by too narrow minded procurement cost oriented weapon system planning is the tendency to overlook such procurement costs which are induced by the procurement of a given weapon system, but which for practical and budgetary purposes are funded out of different chapters and titles. This not only applies to the procurement of additional special or general equipment which is necessary for operation and maintenance of the weapon system in the military units, but occasionally even to weapons which are acquired for the weapon system.

It is obvious that over-emphasizing financial restraints in the development and procurement activities with the resulting necessity for industry to Design to Financial Feasibility can have grave consequences on Operation and Maintenance Costs over the 15 or 20 year life period of a weapon system.

Consequences which military organizations can and partially do draw in order to avoid these negative effects are

- to not only set up project oriented budgets for research, development and procurement, but also for maintenance and perhaps even for incremental costs such as training technical representatives, management support etc.

- to include in the systems oriented research, development and procurement budgets all equipment, weapons and munition which must be procured directly as a consequence of putting a new weapon system into service even though they are funded out of different chapters and titles.

Such additional budgetary ceilings could lead to a situation where a new weapon system is financially feasible with regard to Development and Procurement Costs, however is beyond the set maintenance expenditure limit. Reductions in quantities (if possible), yearly performance levels or design improvements would be the necessary consequence.

Broadening the area of financial limitations could have the following advantages:

- It would make it unattractive to reduce procurement costs by decisions which tend to increase Operation and Maintenance Costs, e.g. to postpone buying basic stock (normally paid for out of the procurement title) until the operation phase of a weapon system or reducing the procurement amount of maintenance equipment.

- It would again place sufficient emphasis on designing to Maintenance Costs aside from prices and Development Costs.

- It would stimulate earlier and closer cooperation between the military and industry in planning and organizing e.g. the maintenance concept and personnel training, as the resulting costs in these areas are just as strongly influenced by the aircraft design (Design to Costs) as by the military organization (Organize to Costs).

- Finally imposing additional financial limitations would make it more meaningful to examine and plan budgetary allocations and financial feasibility over time, especially with regard to the interdependencies between the procurement budget and the postulated project oriented operation and maintenance funds.

The major consequences for costing methodology would be to push forward the development of cost estimating and cost planning models and methods which enable the calculation and presentation of individual cost elements over time and which enable the transformation of the planned Life Cycle Cost categories in the individual years into budget categories in accordance to the household structure. The basic prerequisite for incorporating the time aspect into cost estimating and planning is to define work or functionally oriented LCC-categories. Thus a complete cost structure over time independent of formalistic phase definitions such as Conceptual Phase, Definition Phase, Procurement Phase is guaranteed. Task or functionally oriented cost groups, such as Management, Development, Test, Procurement, Operation, Support etc., each comprising numerous cost categories, run through many or all life cycle phases of a weapon system as indicated in Figure 2. They are the basis for the development of cost planning models over a time axis. As systems and functionally oriented cost plans over time have to be transformed into budgetary plans, crossreferences to budget chapters and titles have to be incorporated into such a model for financial feasibility assessments as is indicated in Figure 3. Due to the completely different purposes and structure of Systems' LCC and the budget this can be quite difficult.

Such dynamic cost models are at present still the exception. They are, however, not only essential for budgetary planning, which per definition is time oriented, but also for analyzing and handling important problems concerning

- timing of phasing-in the weapon system and all equipment, personnel, infractructure concerned,

- the influence of postulated future inflation rates in the countries of a multinational project upon the cost burden of the individual nation as demonstrated in Figure 4,

- the dynamic effects of learning curves on maintenance, of phasing-in and phasing-out procedures, of different procurement policies on stock levels and repurchasing needs etc.

3. Design to Personnel Feasibility

Design to Personnel Feasibility can be viewed as a sub-task of the Design to Cost effort. The available personnel capacity per weapon system in the forces has more and more developed into one of the major constraints on design (complexity, reliability, number of pilots, maintainability) and maximum procurement quantities. However, as planning of personnel within a military service is a problem which remains primarily within the responsibility of the respective service, the dominance of the personnel problem occasionally is underestimated. Reductions in Maintenance Man Hours per Flight Hour as the major parameter determining personnel requirements which can be directly influenced by the design of a future aircraft are occasionally not taken as serious as price and development costs influencing factors. This is enhanced by the fact that improvements in reliability and maintainability normally lead to increases in Research, Development and Procurement Costs where narrow financial limits prevail. On the other hand the positive effect induced in Maintenance Costs by a reduction of Man Hours per Flight Hour needs is not always sufficiently honoured, as (as present regrettable) no strict financial limitations are imposed in this cost category.

If required MHFH-goals however are not achieved, the risk of additional indirect financial loads also increases: In search of ways to reduce the additional load on military and civilian personnel in the forces, military planners can consider increasing e.g. the share of industry in MES 4 category maintenance. Even though some comparisons of industrial versus military costs for the same maintenance programs tend to indicate very similar values, external maintenance, that is maintenance by industrial personnel, increases the load on the defence budget. Personnel in the forces (including civilian personnel) is normally not reduced; expenditures for maintenance are therefore increased roughly by the costs of the industrial personnel which take over the maintenance task. This is a typical example where cost considerations and financial considerations can lead to contrary decisions.

Similar problems crop up when ways and means of raising personnel skill levels are examined in attempting to avoid increasing personnel numbers.

Available personnel being as scarce as financial defence resources, personnel feasibility should be handled as stringently as financial feasibility with all consequences for systems design, procurement and organization. Setting reliability and maintainability incentives and penalties is a step in this direction.

4. Design to Systems' LCC

Design to Systems' LCC comprises far more than Design to Financial Feasibility. The difference corresponds to the difference between costs and expenditures (additional, incremental). The LCC of the total weapon system, which represents all the material, personnel, infrastructure, financial resources and services which are bound or used by the system (opportunity costs) are one of the major decision criteria for trade-off analyses, cost effectiveness assessments of alternatives and force mix analyses. Systems' LCC quantify the total impact of introducing a new weapon system into a military service and are therefore of central concern for service planners responsible for or with an eye on optimizing the structure of their respective services.

The opinion which occasionally can be heard, that, due to the decline of the relative impact of Operation and Support Costs on LCC, these could be neglected, is a grave mistake. The fact that the distribution of costs over Development, Procurement, Operation and Support have shifted from roughly 1 : 3 : 6 to 1 : 4 : 5, as Figure 5 shows, solely proves that strong increases in systems prices and the relative stability of personnel costs due to the limits on available personnel quantities have overcompensated the strong increase in maintenance costs mentioned before (34 % maintenance increase). There is no excuse for neglecting Operating and Support Costs.

The first and basic questions which have to be answered at the outset of Systems' DTC activities are

- which of the major parameter categories are relevant to DTC considerations?
- which are primarily determined by military Define to Cost and Organize to Cost decisions? and
- where should detailed trade-off analyses be conducted? (Figure 6).

As major effort should be concentrated on those parameters which dominantly effect LCC, an impact reference as roughly indicated in Figure 7 should then be established.

Examples of the relative sensitivity of LCC to variations in some of these dominant parameter categories are shown in the next Figures 8 to 11. The parameter with obviously the strongest effect on LCC, the quantity of procured aircraft, in practice is regrettably almost invariable due to operational necessities. As reductions in flight hours per aircraft or per pilot also are only marginally possible and as increases of work load on ground personnel are hardly realistic, the major effort in LCC reduction has to concentrate on the parameter categories 'price' and 'maintainability'. These are the classical Design to Cost areas. They gain additional importance, as possibilities for decisive operational and organizational measures in the services to effect LCC reductions are hardly possible or only marginally effective.

Figure 12 indicates the possible impact on LCC of a major organizational decision: dislocating aircraft in 5 instead of 4 squadrons in the assumed case leads to an increase in O + S Costs of appr. 7 % and of LCC of 4 %. It is obvious that such effects resulting e.g. out of tactical necessities can easily overshadow many DTC advantages.

5. Conclusions

Design to Cost is indisputably an absolutely essential approach to tackling the cost problems as long as the objective does not degenerate to mere Design to Financial Feasibility. DTC must be viewed as an approach to simultaneously

- achieving financial feasibility within all relevant budget categories incl. O + S,
- guarantee personnel feasibility,
- generate minimum Systems' LCC for the performance and effectiveness required.

This can only be achieved if the DTC efforts are accompanied by Define to Cost and Organize to Cost considerations within the field of military options.

DESIGN TO COST IN WS-PLANNING

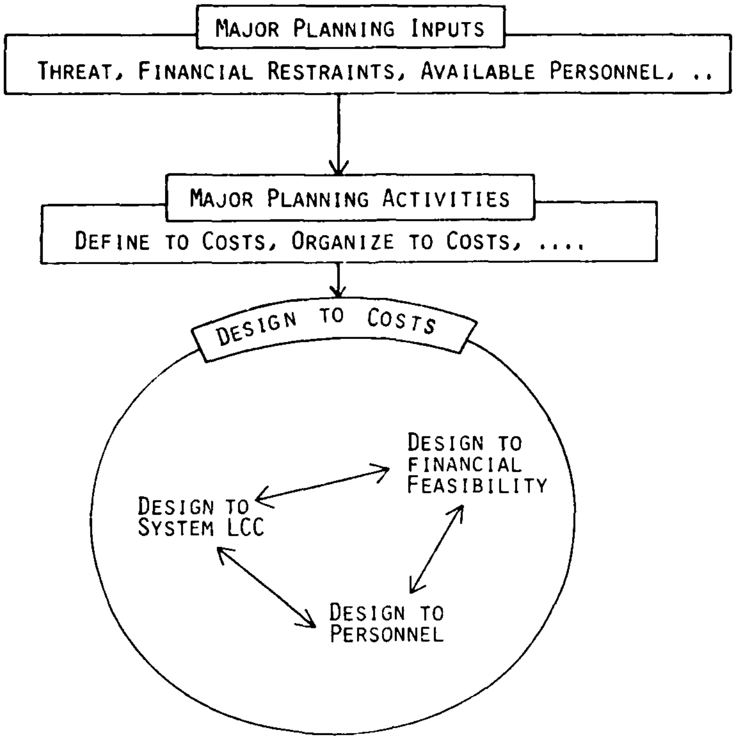

Figure 1

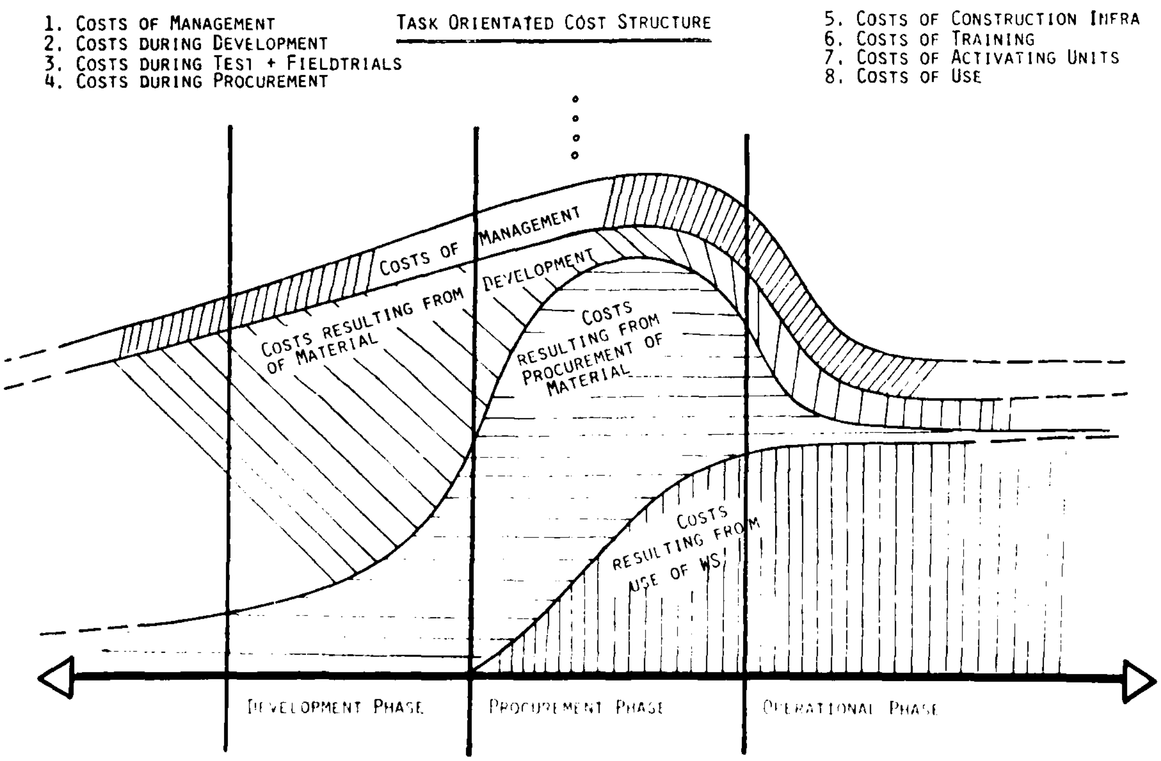

Figure 2

COST - AND BUDGET PLAN

COST - PLAN

Cost-Categorie	Cost Group	Total TDM	Planning Years Year TDM	Year TDM	Year TDM	Year TDM	Year TDM	Year TDM	Year TDM	Year TDM
xxxxxx xxxxxx :	1. Management									
xxxxxx xxxxxx :	2. Development									
xxxxxx xxxxxx :	3. Test									
:	:									
xxxxxx xxxxxx :	8. Support									

EXPENDITURE PLAN

Chapter Titel		Total TDM	Planning Years Year TDM	Year TDM	Year TDM	Year TDM	Year TDM	Year TDM	Year TDM	Year TDM
12/34567	Budget Plan	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -
	Cost Plan									
23/45678	Budget Plan	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -
	Cost Plan									
34/56789	Budget Plan	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -
	Cost Plan									
:	- - - : - - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -

Figure 3

EFFECT OF INFLATION DIFFERENCES BETWEEN NATIONS ON MULTILATERAL PRODUCTION

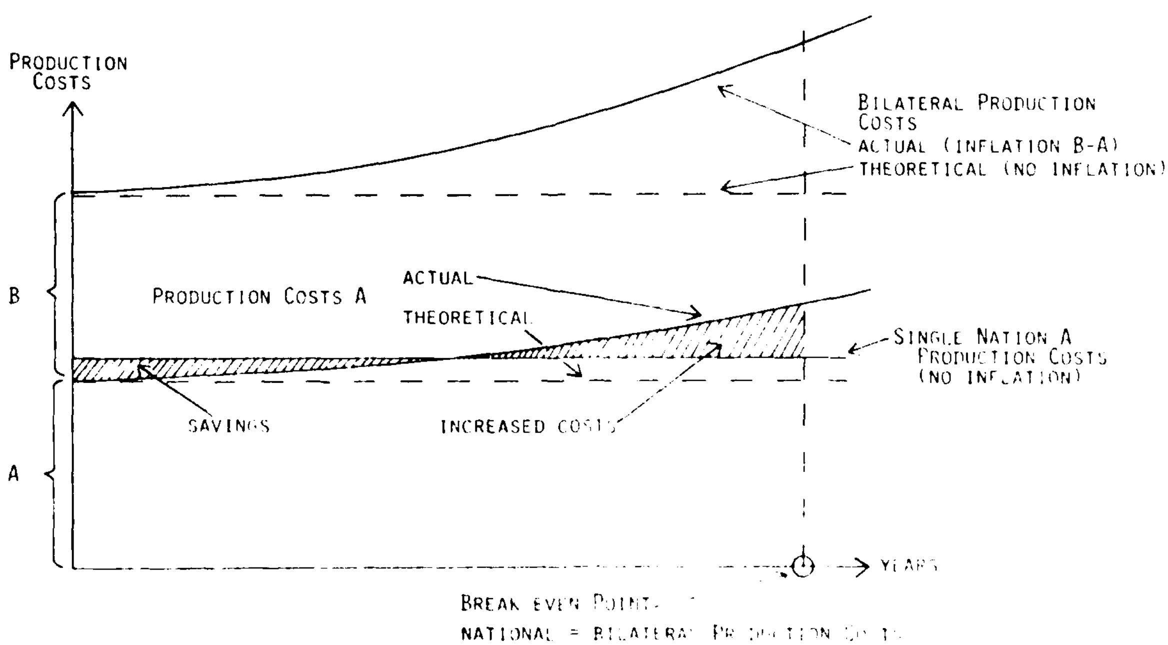

Figure 4

SYSTEM LCC OF A FIGHTER-BOMBER 100 %

	INVESTMENTS	47 %	OPERATION + SUPPORT (15 YEARS)	53 %
MATERIEL	DEVELOPMENT	9 %	O+M A/C (INCL. IND.,EXCL. PERS.)	17 %
			POL A/C	6 %
	PROCUREMENT A/C	24 %	O+M SQUADRON MAT O+M DEPOT/MAINTENANCE MAT	3 %
	PROCUREMENT ADDITIONAL EQUIPMENT, SOFTWARE	12 %	GENERAL MUNITION	1 %
INFRA	CONSTRUCTION	1 %	REPAIR, MAINTENANCE, GENERAL COSTS	
PERSONNEL			TRAINING (CREW)	7 %
	TRAINING BY INDUSTRY	1 %	PERSONNEL SQUADRON	14 %
			PERSONNEL DEPOT/MAINTENANCE	3 %

Figure 5

COST PARAMETERS, DESIGN TO COST AND
TRADE-OFF-ANALYSIS

R,D+P-COSTS ←	PARAMETER CATEGORY →	O+S-COSTS	DTC : D TRADE OFF : T
-	A/C-PRICE	-	D
+	RELIABILITY (MTBF) MAINTAINABILITY (MHFH)	-	D T
-	QUANTITY A/C	-	
+	SIMULATORS	-	T
+	FIRST STOCK	-	T
+	QUANTITY MAINT. EQUIPMENT	-	T
-	INTERNATIONAL COMMONALITY OF A/C	-	D
	COMMONALITY GROUND EQUIPM. TO PREDECESSOR	+	D T
	FLIGHT HOURS	.	
-	DISLOCATION A/C	-	
	.		
	.		
	.		
	.		

Figure 6

Impact Areas of Major Cost Parameter Categories

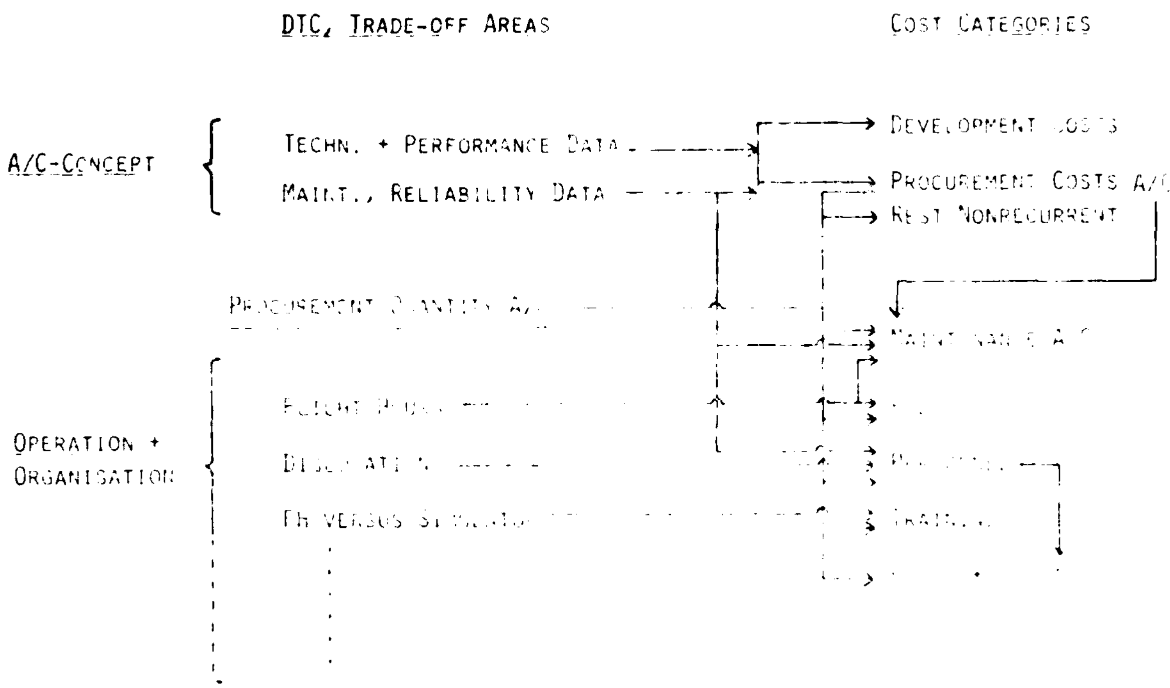

Figure 7

Parametric Variation

Decision for a 10 % more Expensive A/C

Development and Procurement Costs	+ 9,7 %
Operating and Maintenance Costs	+ 3,3 %
Life Cycle Costs	+ 6,4 %

Relative Sensitivity $\dfrac{\triangle \text{LCC in \%}}{\triangle \text{Price in \%}} = 0{,}64$

Figure 8

PARAMETRIC VARIATION

DECISION FOR 10 % INCREASE IN FLIGHT HOURS

DEVELOPMENT AND PROCUREMENT COSTS	± 0 %
OPERATING AND MAINTENANCE COSTS	+ 5,2 %
LIFE CYCLE COSTS	+ 2,7 %

RELATIVE SENSITIVITY $\frac{\Delta\ LCC}{\Delta\ FH} =$ 0,27

Figure 9

PARAMETRIC VARIATION

REQUEST FOR A/C WITH 10 % IMPROVED MHFH-VALUES

DEVELOPMENT AND PROCUREMENT COSTS	(+ 1 %)
OPERATING AND MAINTENANCE COSTS	- 3 %
LIFE CYCLE COSTS	- 1-2 %

RELATIVE SENSITIVITY $\frac{\Delta\ LCC}{\Delta\ MHFH} =$ - 0,15

Figure 10

PARAMETRIC VARIATION

DECISION FOR 10 % ADDITIONAL NO. OF A/C

DEVELOPMENT AND PROCUREMENT COSTS	+ 8 %
OPERATION AND MAINTENANCE COSTS	+ 6,7 %
LIFE CYCLE COSTS	+ 7,3 %

RELATIVE SENSITIVITY $\frac{\Delta \text{ LCC}}{\Delta \text{ No.A/C}} = 0{,}73$

Figure 11

PARAMETRIC VARIATION

DISLOCATION OF 160 A/C IN 5 INSTEAD OF 4 SQUADRONS

DEVELOPMENT AND PROCUREMENT COSTS	(+ 1 %)
OPERATING AND MAINTENANCE COSTS	+ 6,6 %
LIFE CYCLE COSTS	+ 4 %

Figure 12

IMPACT OF MAINTAINABILITY ON LIFE CYCLE COSTS

by G.R.Thornber
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1. Introduction

The interpretation of the definitions of the varied parameters used in assessing maintainability can have a significant effect on the quantification of the effect on Life Cycle Cost. One possible interpretation is considered and the results obtained using this are indicated.

Methods of assessing maintainability as applied to two international collaborative military aircraft are considered and some of the lessons and problems encountered are touched upon.

2. Definitions

There has been much discussion on the various "abilities" associated with aircraft, i.e. maintainability, reliability, serviceability, availability and survivability, and it is sometimes difficult to know where one ends and the other starts. Manufacturers' brochures are in the habit of making great play of these "abilities" without defining what is meant, leaving the reader to make his own - often incorrect - assumptions. This paper considers one possible set of definitions.

Maintainability is a characteristic of design and installation which is expressed in terms of ease and economy of maintenance and therefore boils down to the number of manhours it takes to do a job. Fig.1. illustrates this definition. The total number of manhours to maintain an aircraft is the summation of the individual tasks and is usually expressed as manhours per flying hour. It is inevitably tied in with reliability, since this defines the number of times a particular job has to be done within a given timescale. Occasions may arise when an aircraft which is easy to maintain has a high manhour content because an item needs changing frequently due to its unreliability.

Often, in the requirements of military aircraft, there is a specific target related to maintainability. Typically, these will state that the total manhours per flying hour will not exceed a certain value. This may be broken down further into time spent on the aircraft and time spent off the aircraft, together with scheduled and unscheduled tasks. Scheduled tasks may be broken down even further into such items as before flight, between flight and after flight inspection. Fig.2. illustrates a typical breakdown for a military aircraft. Alongside this maintenance aim there may also be reliability targets since maintainability and reliability go hand in hand.

It is necessary to look more closely at the manhour content. Clearly, once an item has been removed it has to be repaired expending further manhours. In order to be consistent, it has been the practice to utilize the breakdown that is applied in the Royal Air Force, since most of this work is done in conjunction with them. This assumes that any tasks that can be carried out at base (1 & 2 levels) are counted in the manhours, whereas depot (3rd level) and return to manufacturer (4th level) are not- the manhours are, however, included in the overall life cycle costs as will be seen later.

It is further necessary to distinguish between direct and indirect manhours. It is important in this context to understand that direct manhours refers to "spanner-in-hand" time and indirect to that additional time that makes up the total it does not refer to overheads. To a User the total manhours are important but the ratios of direct to indirect vary greatly depending on circumstances. Indirect manhours often include items way outside the manufacturer's control. On the other hand, it is very rare that direct manhours are measured - for instance the average "job-card" used to record a job is almost invariably total time, including such items as getting the necessary tools, ground equipment and even waiting-time in some cases.

Calculations, therefore, are almost invariably done on direct manhours and an allowance made to factor these figures, in order to obtain the total - factors of 2 or 3 may be involved in some cases. From these total manhours it is possible to estimate the manning requirements. These manning figures may need adjusting to allow for the practicalities of life. For instance, it may be that the maintenance manhours show that half a man would be adequate to cover the workload (say, instrument fitters for a small squadron of light aircraft). This would probably mean provisioning for two men to cover for illness, leave periods, etc. The numbers of men may now be fed into the cost calculations.

3. Impact on Cost

It can be shown that using the preceding definition it is possible to break down the maintenance costs of an aircraft into four basic areas. These are

Maintenance Manpower
Fuel and Oil
Consumables
Spares and Repairs.

This is illustrated at Fig.3., using typical European rates and prices. The costs

shown here are only those attributable to the task itself and do not include "overheads" and supporting facilities, i.e. Cookhouse, Transport Station, etc.

The block for spares and repairs includes the cost of replacement items on the one hand and the total cost of repairs carried out, either at depot or supplier level, on the other hand. In both cases the cost of the manpower involved is included in the spares and repairs cost.

It can be seen that out of the yearly cost about 30% is fuel, 50% is spares and repairs, 5% is consumables such as tyres, brakes, oxygen and the like, and the rest, 15%, maintenance manpower. This assumes that the task is being manned in an economic fashion. There may be strategic reasons for this not being true, particularly now that operation from shelters is increasing. This picture remains surprisingly similar for a variety of different aircraft, ranging from a basic trainer to a low level strike aircraft. To further put this in context, these yearly operating costs look like about 7% of aircraft first cost (excluding R and D). Again, this is reasonably constant, for a given generation of aircraft.

The above costs indicate that the overall effect of improving the reliability aspects may be more significant than maintainability improvements. However, it is important to remember that the cost of achieving improved reliability, which must be included in other segments of the overall life cycle may be very much greater than the cost of introducing a maintainability improvement.

4. Methods of Assessment

The ways in which the approach to maintainability has been evolved over a period of some 15 years will now be considered.

4.1 S.E.P.E.C.A.T. Jaguar

The Anglo-French Jaguar aircraft was the first aircraft in the U.K. on which maintainability targets were set in the original design requirement. A finite direct manhour content was quoted for the 1st and 2nd line tasks, based on a certain number of sorties per day. This is similar to the breakdown shown at Fig.2.

A three-pronged approach was made towards maintainability, as illustrated at Fig.4. Firstly, in the design stage, close collaboration between the design staff, User representatives and Product Support engineers, ensured that a critical look was taken at engineering aspects. This included appraisal of mock-ups and prototypes. Secondly, the times for all maintenance tasks were considered theoretically and thirdly, a series of controlled measurements were taken to give some confidence in the calculation. Feedback throughout the process was essential.

In assessing the timings for maintenance tasks a modified form of the M.T.M. system was used in which all movements associated with a task are broken down into basic elements. A series of Primary Standard Data sheets were produced, typically illustrated at Fig.5. These enabled the times for individual actions to be calculated. These are then summated to give the total times. The method proved to be quite effective but was also very time-consuming. It is perhaps of interest to note that after some weeks' work to evaluate the time for engine removal, the results tied in very closely with the practical demonstration and with an on-the-spot assessment of a skilled fitter!

The practical assessment took place in two main areas, the French VAMON and the R.A.F. Service Maintainability Assessment Exercise, in which the Customer undertook a variety of maintenance tasks on an early standard of aircraft. Each of these exercises lasted several weeks and many changes were introduced as a result. However, these exercises were done under controlled clinical conditions and the main feedback was with respect to ease of maintenance rather than absolute times. No real service exercise has been carried out to prove the figures, but in qualitative terms some complimentary remarks have been made which are of comfort. (See Fig.6.).

4.2 Panavia Tornado

The next project was the Anglo-German-Italian Tornado, where the requirements were somewhat more precise in their detail, but still refer to direct manhours. The breakdown is shown in Fig.7. There is also a requirement to achieve a given percentage of faults cured within a given timescale. In the case of Jaguar, the majority of equipments, particularly avionics, are Government Furnished, that is to say, the MoD develop and procure the equipment, with the airframe manufacturer merely fitting them. Maintainability features of the equipments are the responsibility of the development agency and to some extent, the suppliers' inputs had to be accepted. However, in the case of Tornado, where Panavia - the Tri-National Weapon System Contractor - have overall Weapon System Responsibility and are responsible for equipment procurement, it was possible to lay down the rules under which the equipment manufacturer carried out a maintainability analysis on his own equipment which was then fed into the total weapon system Maintainability Analysis.

From the reliability of the equipment, together with any appropriate test and repair times, it is clearly possible to predict the maintenance manhour content of individual items. This is a formalised process whereby Maintenance Analysis Sheets are filled in for each function, system by system. A Maintenance Analysis Sheet is illustrated at Fig.8. These are then gathered together in the form of a Maintenance Analysis Report which is our analysis of the total Weapon System. Fig.9. shows a page from the Maintenance Analysis Report - it should be noted that the systems and values are hypothetical.

The basic concept for Tornado is that of "On-Condition" Maintenance. However, there are instances where it may be necessary to recommend some scheduled work. If this is so, the request has to be submitted to the Customer on a Scheduled Maintenance Approval Form (Fig.10.). However, it is the decision of the User Nations as to whether these recommendations are applied. The maintainability requirements upon the Contractor are based on the Contractor's recommended servicing procedures and it is possible to envisage divergences occurring with the Analysis Report incorporating procedures that are recommended but not accepted by the User!

A further complexity exists due to the different maintenance policies that exist in the different User Air Forces. Whereas the R.A.F. have always written their own Servicing Schedules based upon, but not necessarily adhering to, the Contractor's recommendations, the German Air Force requires the manufacturer to write the Schedules, thus a differing maintenance concept can exist between individual Nations.

The preceding paragraphs have largely been concerned with the theoretical assessment of maintainability; the proving of the values should now be considered. A series of Formal Maintainability Demonstrations have taken place under which a variety of maintenance tasks are performed by the manufacturer in front of witnesses from the Customer. In general, these trials have shown reasonable agreement between actual measurements and theoretical calculations. However, it should be said at this stage that these trials have taken place in a somewhat clinical environment on an air vehicle in a new condition and the numbers would not necessarily be reflected in a service environment on an aircraft where wear and tear existed. For instance, it is a very different thing removing a series of well-greased, new bolts, as opposed to some that have become firmly embedded and the heads of which have been worn!

Having said the above, is there any value in doing a proper data gathering exercise under operational conditions? There are arguments to be said on both sides. It is perhaps worth looking at what the results of such an exercise really mean. By the time the stage of doing such a data gathering exercise has been reached, which must be after the aircraft has been in service for some time, it is possible that any lessons learnt will be too late for the introduction of significant modifications in a cost-effective manner. Where it may be of considerable benefit is in the next generation of aircraft. The value here is in proving that the method of assessment provided accurate values, thereby increasing the credibility of the methods for use in future projects. It is, however, considered that the actual values obtained will not be read across because the advancement of technology will introduce new maintenance concepts. An example of this can be seen in the increasing reliance on Built In Test Equipment (B.I.T.E.). This is designed to increase the ease with which faults may be diagnosed. There may also be an increasing emphasis on the ability to test following fault rectification - perhaps "testability"!

It could, however, be argued that the Formal Maintainability Demonstrations carried out in a "test environment" are more suitable, to prove the calculations which were based on a somewhat idealised situation in the first place.

An exercise carried out in an operational environment might lead to a better definition of the difference between direct and indirect manhours but these would only be relevant to the circumstances of that particular exercise. They could be totally different under alternative circumstances.

The calculations in themselves are also of value in that they allow for a theoretical examination of a variety of different installations in any new aircraft. For example, given the choice of an engine installation that allows removal either downwards or rearwards, the argument can be extremely emotive if it is not possible to present calculations which show the relative merits in terms of maintenance manhours per flying hour.

5. Summary

Summarising, therefore, it is considered that it is as important to emphasise the need for improved reliability of equipment and the ability to diagnose faults, than to over-emphasis the maintainability aspects. None the less, ease of access and ability to remove items quickly are of paramount importance. In connection with this, it should be remembered that the requirements for normal day to day operation in peace time may be very different from the requirements in the event of conflict. In this situation, availability of aircraft is perhaps the yardstick that should be used. In all probability, the availability of spare line replaceable unit

will also be a more significant parameter than time to repair individual L.R.U.s. Assessments of maintainability have been carried out in which theoretical and practical timings are compared. These indicate that the calculations bear a reasonable relationship to the actuals achieved, but this is true only in a test environment.

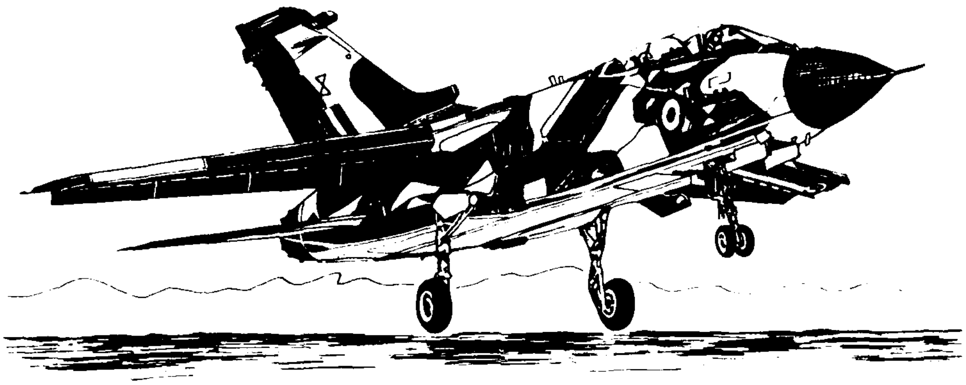
In terms of impact on life cycle costs, the ratio of direct to indirect man-hours is a significant parameter that may vary extensively from circumstance to circumstance and is currently extremely difficult to evaluate.

6. Acknowledgement

The views expressed in this paper are the author's personal views and may not necessarily reflect those of British Aerospace. The author gratefully acknowledges British Aerospace's agreement to present this paper

1st May, 1980

Maintainability is a characteristic of equipment design and installation which is expressed in terms of ease and economy of maintenance, availability of the equipment, safety, and accuracy in the performance of maintenance actions.



Maintainability Definition

Figure 1

PRE FLIGHT SERVICING		HOURS
TURN ROUND		HOURS
AFTER FLIGHT SERVICING		HOURS
Number of Sorties		
TOTAL FLIGHT-LINE SERVICING		HOURS
DEFECT RECTIFICATION		HOURS
PERIODIC SERVICING		HOURS
WORKSHOP SERVICING		HOURS
TOTAL MANHOURS PER FLYING HOUR		HOURS

Figure 2

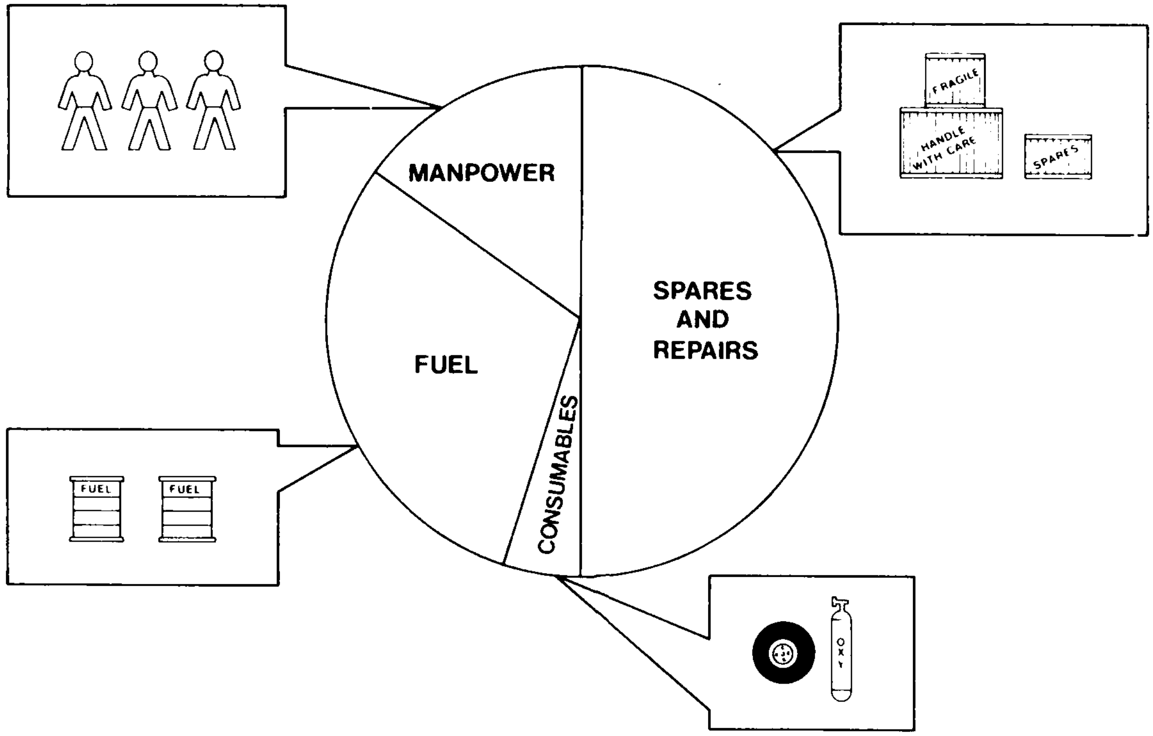


Figure 3

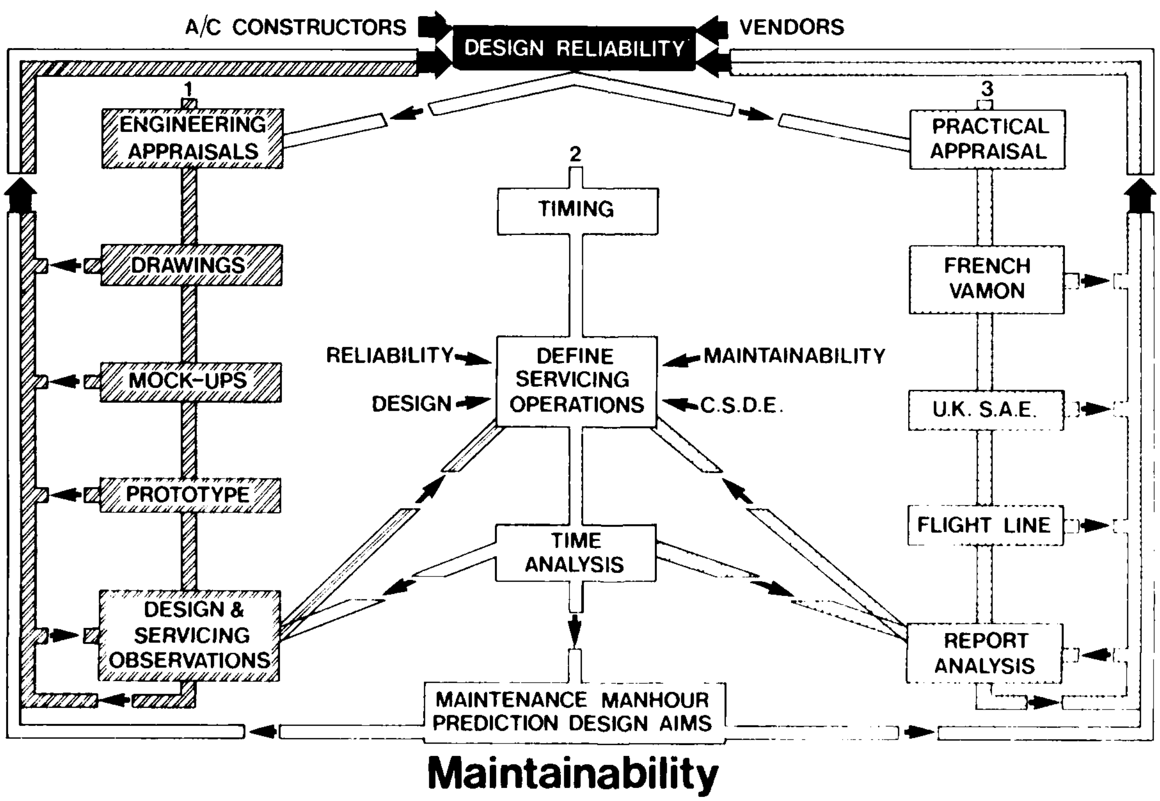
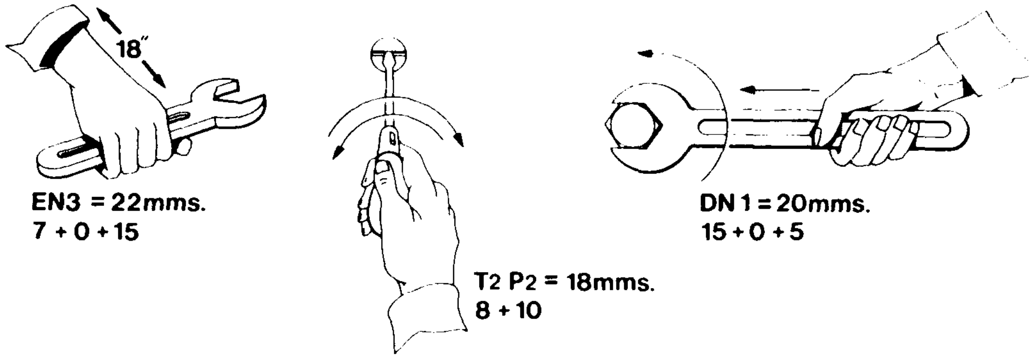


Figure 4



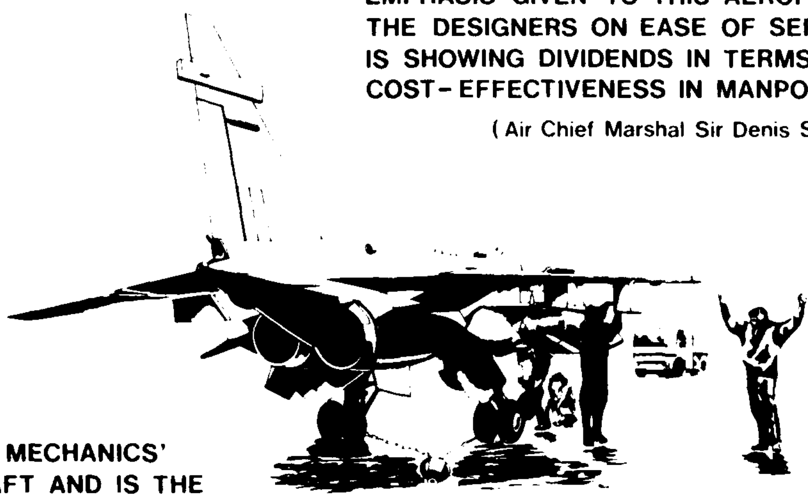
TARGET	GRASP	DISTANCE
E = 7 A = 10 D = 15	N = 0 J = 5	0 (>12") = 0 1 (12"–24") = 5 2 (24"–36") = 10 3 (<36") = 15
TURNING	**FORCE/WEIGHT**	**MISC.**
T_1 = 6 T_2 = 8 T_3 = 10	P = 5 Weight = $W/_5$ Weight = $W/_{10}$	Steps S = 8 Bend UD = 35 Difficulty d = 3 Look L = 5

P.S.D. Basic Value

Figure 5

"EMPHASIS GIVEN TO THIS AEROPLANE BY THE DESIGNERS ON EASE OF SERVICING IS SHOWING DIVIDENDS IN TERMS OF COST-EFFECTIVENESS IN MANPOWER"

(Air Chief Marshal Sir Denis Smallwood)



"IT IS A MECHANICS' AIRCRAFT AND IS THE EASIEST AIRCRAFT TO WORK ON THAT WE HAVE HAD FOR YEARS"

(Crewchief)

Maintainability

Figure 6

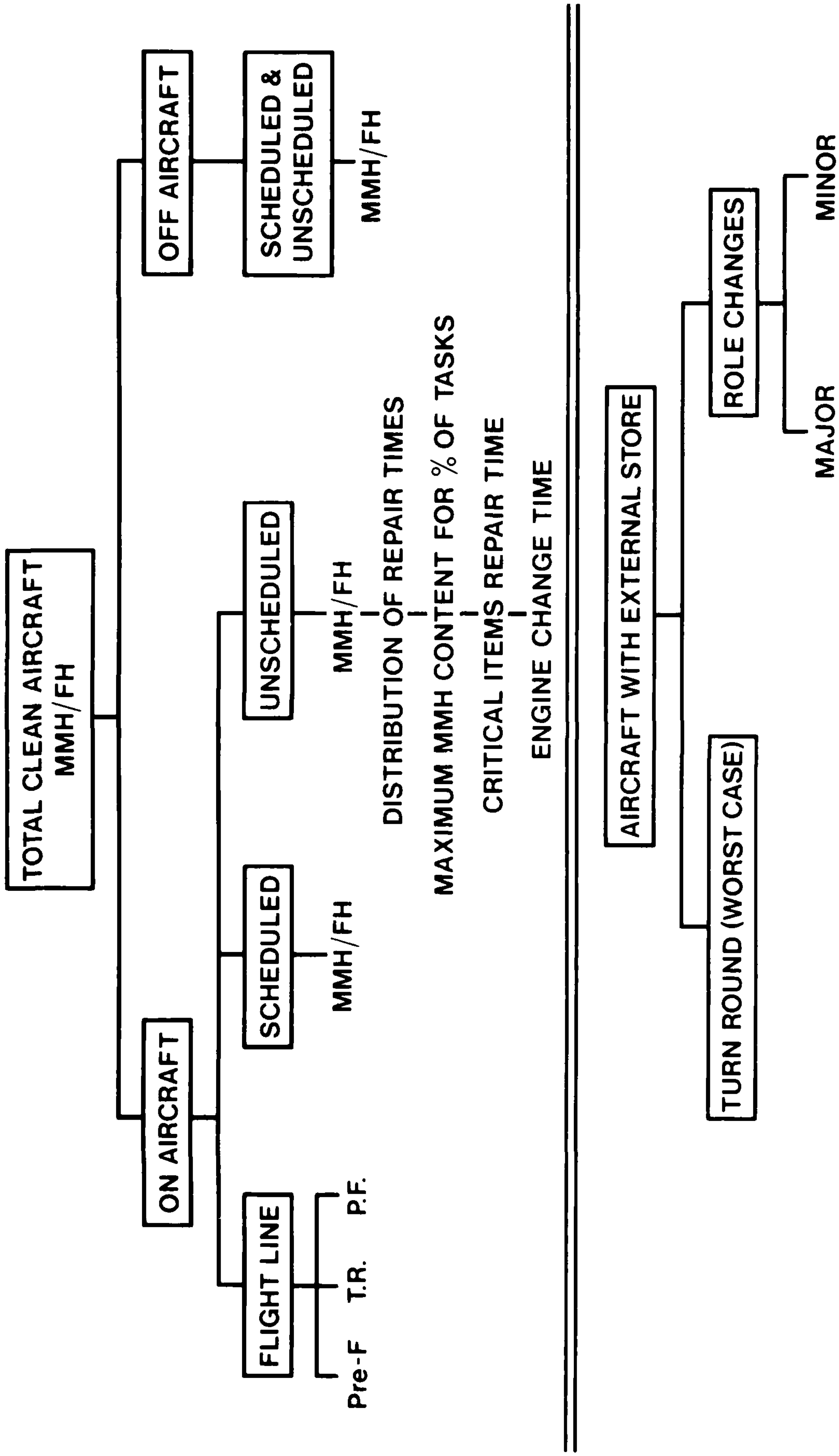

TOTAL CLEAN AIRCRAFT
MMH/FH
ON AIRCRAFT
OFF AIRCRAFT
FLIGHT LINE
Pre-F
T.R.
P.F.
SCHEDULED
MMH/FH
UNSCHEDULED
MMH/FH
SCHEDULED & UNSCHEDULED
MMH/FH
DISTRIBUTION OF REPAIR TIMES
MAXIMUM MMH CONTENT FOR % OF TASKS
CRITICAL ITEMS REPAIR TIME
ENGINE CHANGE TIME
AIRCRAFT WITH EXTERNAL STORE
TURN ROUND (WORST CASE)
ROLE CHANGES
MAJOR
MINOR

Figure 7

1.

MAINTENANCE ANALYSIS SHEET

AUTHORISATION

NOMENCLATURE | PREPARED BY | CONTROL NO. (WUC) | ISSUE

NOMENCLATURE FOR NEXT HIGHER ASSY | QTY. PER SYSTEM | A/C MODEL | A/C EFFECTIVITY | DATE

2. MANUFACTURER	3. SPEC. NO. / 4. P/N	5. PUB REQUIREMENTS	6. MMH / FH SCHEDULED	UNSCHEDULED

7. FUNCTION	8. REQ. NO.	MAINTENANCE CONCEPT DESCRIPTION

9. MAS CHANGE RECORD

ISSUE	REASON FOR REVISION	SHEETS AFFECTED

PANAVIA

COVER SHEET I

SHEET _____ OF _____

Figure 8

SCHEDULED MAINTENANCE — TABLE 3 — DATE 02/04/80 — PAGE NO. 84

WUC	NOMENCLATURE TRADE LV	ACTIVITY PREP	REMOVE	A/C APPLICABILITY TASK	REFIT	ON/OFF A/C TEST	SMAF NO FINISH	STATUS TOTAL	FREQ MMH/FH	QTY
SYSTEM	ATMOSPHERIC RESEARCH EQUIPMENT									
9800A	ATMOSPHERIC RESEARCH EQUIP	OPER CHECK		XXXXXX		ON	98 -01		100	01
	MECH 2	0.00	0.00	60.00	0.00	0.00	0.00	60.00		
	ELEC 2	0.00	0.00	60.00	0.00	0.00	0.00	60.00	.020000	
	ELAPS	0.00	0.00	60.00	0.00	0.00	0.00	60.00		
		GS	GT	IS	IT	BS	BT			
SYSTEM	980	0.020000	0.020000	0.020000	0.020000	0.020000	0.020000			
SYSTEM	PRESSURE RECORDING EQUIPMENT									
9810A	PRESSURE RECORDING SYSTEM	PRESS TEST		XXXXXX		ON	98 -02		100	01
	MECH 2	0.00	0.00	30.00	0.00	0.00	0.00	30.00	.005000	
	ELAPS	0.00	0.00	30.00	0.00	0.00	0.00	30.00		
9811A	SENSOR, PRESSURE	CALIBRATE		XXXXXX		ON	98 -03		500	06
	MECH 1	15.00	0.00	0.00	0.00	0.00	26.00	41.00		
	ELEC 2	0.00	0.00	12.00	0.00	0.00	0.00	12.00	.010600	
	ELAPS	15.00	0.00	12.00	0.00	0.00	26.00	53.00		
		GS	GT	IS	IT	BS	BT			
SYSTEM	981	0.015600	0.015600	0.015600	0.015600	0.015600	0.015600			
SYSTEM	TEMPERATURE RECORDING EQUIP									
9820A	TEMPERATURE RECORDING EQUIP	PRESS TEST		XXXXXX		ON	98 -02		100	01
	MECH 2	0.00	0.00	10.00	0.00	0.00	0.00	10.00	.001667	
	ELAPS	0.00	0.00	10.00	0.00	0.00	0.00	10.00		
9821A	SENSOR, TEMPERATURE	CALIBRATE		XXXXXX		ON	98 -03		500	07
	ELEC 2	0.00	0.00	18.00	0.00	0.00	0.00	18.00	.004200	
	ELAPS	0.00	0.00	18.00	0.00	0.00	0.00	18.00		
9822A	RECORDER (UK A/C ONLY)	REM FOR OH		----XX		OFF	98 -04		1000	01
	AVION 3	0.00	0.00	940.00	0.00	0.00	0.00	940.00	.015667	
	ELAPS	0.00	0.00	2400.00	0.00	0.00	0.00	2400.00		

Figure 9

SCHEDULED MAINTENANCE APPROVAL FORM　　　　SERIAL NO.

NOMENCLATURE	SYSTEM CODE

MANUFACTURER	SPEC.NO.	PART NO.
PRIME CONTRACTOR		

LOCATION	PERIODICITY	MAINTENANCE TASK
ON A/C		
OFF A/C		

JUSTIFICATION

PRIME CONTRACTORS ENGINEERING	PRIME CONTRACTOR	PMWG ACKNOWLEDGMENT	NAMMA APPROVAL
ISSUE	DATE	DATE	DATE

NAMMA FORM [illegible]

Figure 10

ESTIMATION OF RELATIVE TOTAL COST FOR AIRCRAFT SYSTEMS

by
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SUMMARY

To achieve optimum solution for system concept and equipment selection for transport aircraft, the comparison of the total costs of alternatives offers decisive decision criteria. Accordingly, it is important that a suitable method for determining the relative total costs (fixed and operating costs) is available.

Once a decision has been reached in favour of a system concept, the data for the subsystem/equipment that are associated with the operating costs must be laid down as guaranteed values in the technical specifications/contracts with the equipment suppliers.

During the operating phase a clear statistical comparison must continuously be accomplished between the target and the actual values in order to ensure that any deviations and the causes of such deviations can be detected and eliminated. For this purpose, it is necessary to have an agreed procedure between operator, aircraft manufacturer and equipment supplier.

ABBREVIATIONS

A/C	Aircraft
BITE	Build IN TEST Equipment
Engr	Engineer
f	Function Of
FH	Flight Hour
GSE	Ground Support Equipment
LRU	Line Replaceable Unit
MTBD	Mean Time Between Defect
MTBUR	Mean Time Between Unscheduled Removal
OH	Operating Hour
Qty	Quantity
Situ	in its original situation

1. INTRODUCTION

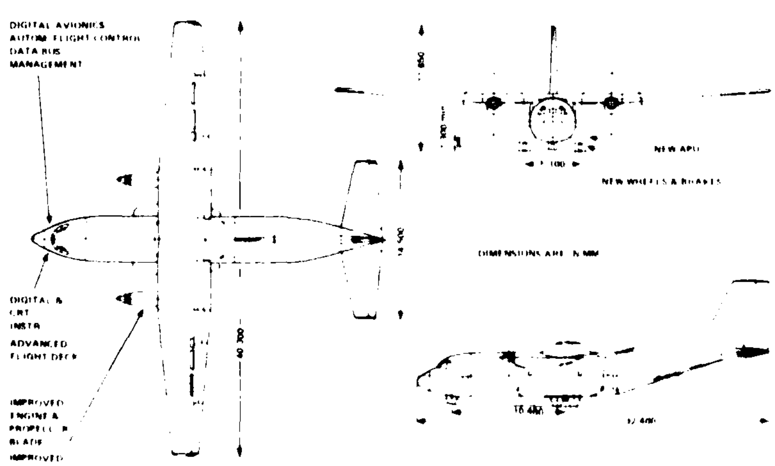
The following hypothetical case will be used to illustrate the demand for developing a suitable prediction method for the total costs and for the application of such a method.

> "Superannuated military transport aircraft have to be rejected between 1990 and 1995. The required transport capacities correspond to aircraft of the Transall C160 or Hercules C130 category."

With regard to the successor the following three fundamental alternatives arise:

VFW

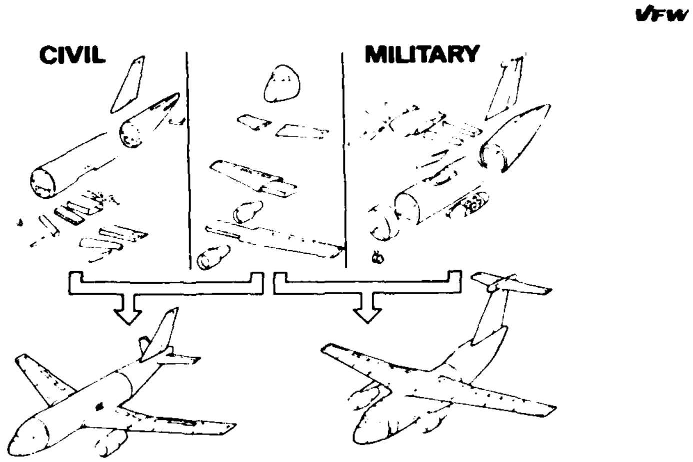
I To produce new aircraft of the existing type with certain improvements (see FIG. 1)



1 TRANSALL C-160
POSSIBLE DESIGN IMPROVEMENT EASY TO INTRODUCE

II Modification of civil transport aircraft or use of larger parts/ components from civil aircraft

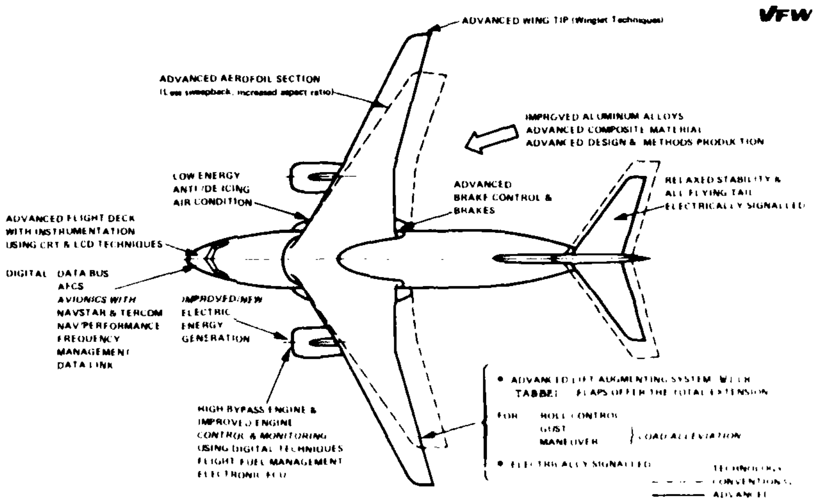
(see FIG. 2)



II MODIFIED CIVIL TRANSPORT AIRCRAFT OR USE OF COMPONENTS FROM CIVIL AIRCRAFT

III Transport aircraft, new design, using advanced technology in line with all tactical requirements and with special view to low operating costs and high degree of dispatch reliability/ clear for action

(see FIG. 3)



III TRANSPORT AIRCRAFT, NEW DESIGN, USING FUTURE TECHNOLOGY

These alternatives have to be technically elaborated down to component level in order to obtain data with sufficient confidence level for the cost estimation method.

The entire process leading to the decision as to which of the three given alternatives represents the most suitable solution, involves a comparison and assessment of the following criteria

- FULFILMENT OF TACTICAL OR FUNDAMENTAL TECHNICAL REQUIREMENTS
- TOTAL COST SITUATION (with which the following chapters shall deal).

2. COST ESTIMATION METHOD

2.1 The method described below does not give any fundamental novelty regarding cost estimation but tries to give a clear summary of familiar facts in order to illustrate a means of having a pragmatic and systematic instrument for relative cost estimation.

It should be noted that this method involves considerably more elaboration in the definition phase with a view to technical itemization and determination of cost.

The advantage of this method is, however, that it yields a sufficiently confident result in terms of the cost relation between various alternatives and thus an exacter basis for decisions as well as target values for the realization and utilization phase.

2.2 The survey FIG. 4 shows the COST ELEMENTS and CALCUALTION STEPS for the

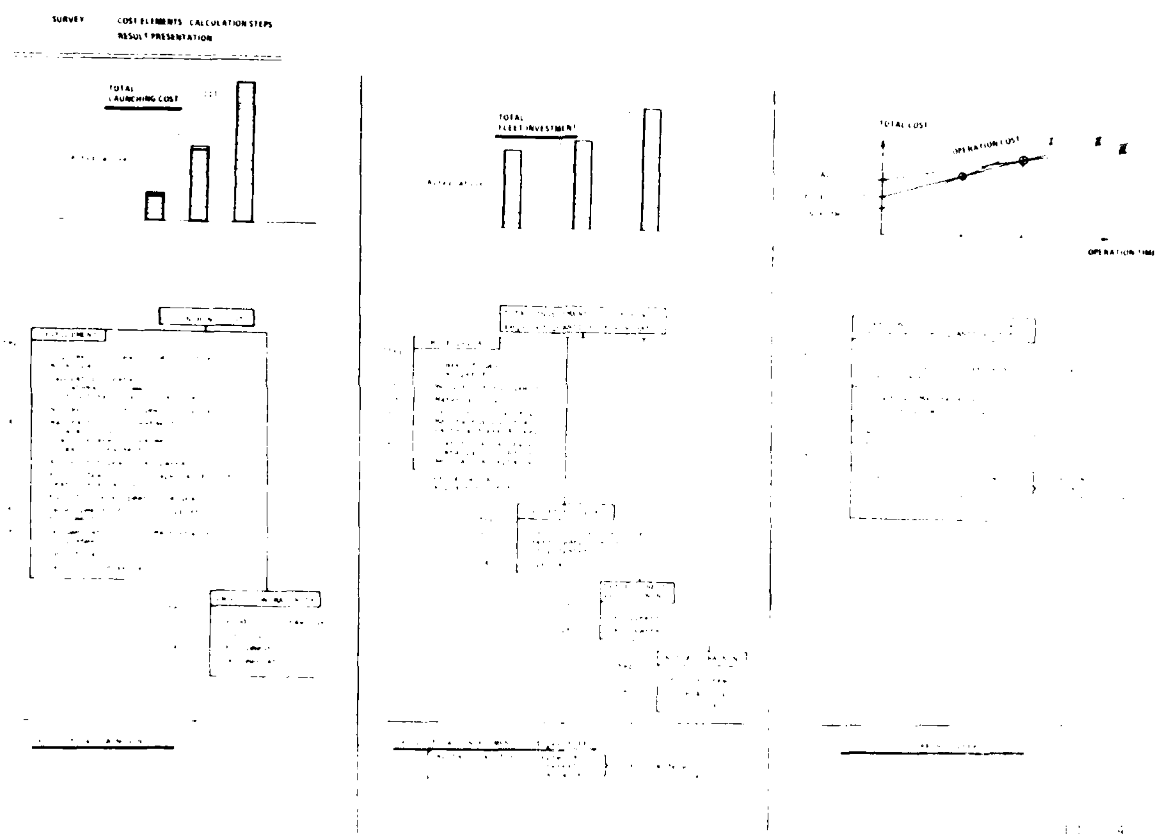
- o LAUNCHING
- o FLEET-INVESTMENT
- o OPERATION

PHASES, which must be taken into consideration per system type when comparing the system alternatives.

The determined values are here primarily to be seen as relative costs within the scope of a comparison.

The result for the LAUNCHING and FLEET-INVESTMENT costs per system alternative is best illustrated by means of COST BAR CHARTS, to show where the largest differences in cost exist.

Drawing up the CUMULATIVE OPERATING COSTS as a function of the OPERATING TIME, starting out from the fleet-investment costs, the points of intersection will then mark the operation time phase where each special alternative represents the optimum total cost solution.



2.3 The tables in FIG. 5 to FIG. 12 reveal the following per

cost element = calcualtion step

for the cost determination:

- o work breakdown and extent/content respectively
- o function of cost factors
  (detailed formula are not presented here)
- o breakdown of cost factors into variables and constants
  (the individual values/data/results should be entered here)
- o up to which level - subsystem or component - costs are to be determined
  (if costs are determined to equipment level, the total per subsystem must then be formed)

CALCULATION MATRIX for the system/equipment relevant steps only

LAUNCHING COST

Step No.	Cost Element	Content & Function	Factors: Variable	Factors: Constant	Level	To be calculated down to level, resp.: System / Sub-system	Set / Component
1	- Engineering	o system definition & specification o equipment specification & procurement o reliability & maintainability analysis o test requirements, program, attendance, data evaluation for - laboratory test - ground test on A/C - flight test o instruction for adjustment, rigging o support production, certification Σ Eng.Hour / Rate/Eng.Hour / Burden Factor	Engineer-Hour	Rate/Engr.Hour Burden Factor	I II III		
	- Design	o initial design o production drawings o stress, fatigue analysis o installation instruction o support production, certification Σ Engr.Hour / Rate/Engr.Hour / Burden Factor	Engineer-Hour	Rate/Engr.Hour Burden Factor	I II III		
	- Mock-Ups	o material o production Σ Labour Hour / Labour Rate / Material Cost / Burden Factor	Labour Hour, Material Cost	Labour Rate, Burden Factor	I II III		
2	Laboratory Test	o test facility - definition, design - purchase material, equipment - parts production, assembly adjustment o test installation, test execution o test reports Σ Engr.Hour / Rate/Engr.Hour / Material Equipment A/C Parts Cost / Labour Hour / Labour Rate / Burden Factor	Engr.Hour, Material, Equipment, A/C Parts Cost Labour Hour	Rate/Engr.Hour, Labour Rate, Burden Factor	I II III		

Step No.	Cost Element	Content & Function	Factors: Variable	Factors: Constant	Level	To be calculated down to level, resp.: System / Sub-system	Set / Component
[illegible]	Equipment [illegible] Non Recurring	Cost per new or modified unit subsystem type Σ Non Recurring per new/mod unit type [illegible]	[illegible] of new or modified unit types	[illegible]	I II III		
[illegible]	Manufacturing [illegible]	[illegible] design [illegible] material, equipment [illegible] assembly Σ [illegible] / Rate/[illegible] Hour / Material Equipment [illegible] / [illegible] / Labour Rate / Burden Factor [illegible]	Engr. Hour, Material, Equipment [illegible] Labour Hour	Rate/Engr.Hour, Labour Rate Rate, Burden Factor [illegible] from 4	III		
	[illegible]	[illegible] parts & pre-assembly, [illegible] Material [illegible] / Labour Rate / Burden Factor	Material, Labour Hour, Equipment [illegible]	Labour Rate, Burden Factor	II III		
[illegible]	Flight Testing	[illegible] flight test & development [illegible] [illegible] design [illegible] material & equipment [illegible] test program [illegible] [illegible] test [illegible] test reports Σ [illegible] / Rate/Engr.Hour / Material Equipment [illegible] / Labour Hour / Labour Rate / Flight Hour / Flight Hour / Burden Factor	Engr.Hour, Material, Equipment [illegible] Labour Hour, Flight Hour	Rate [illegible], Labour Rate [illegible] Burden Factor	I II III		

[illegible] No.	[illegible] Element	Content & Function	Factors: Variable	Factors: Default	[illegible]	[illegible]	[illegible]
[illegible]	[illegible] Development [illegible]	[illegible] engineering and design [illegible] prototypes [illegible] ≙ % from [illegible] % from [illegible]		% from [illegible]	I II III		
[illegible]	Development [illegible] Support [illegible] Test and Special [illegible]	[illegible] design [illegible] [illegible] purchase of necessary [illegible] for flight testing [illegible] ≙ [illegible] Hour / Rate [illegible] / Rate Tester [illegible] / Burden Factor	[illegible]	Rate [illegible] Burden Factor	I II III		
[illegible]	[illegible] Maintenance [illegible]	[illegible] } [illegible] [illegible] ≙ [illegible] engineering & design		% from [illegible] engineering & design	I II III		
[illegible]	[illegible]	[illegible] report [illegible] ≙ % from [illegible] engineering & design		% from [illegible] engineering & design	I II III		
[illegible]	Technical Risk Factor	- A risk factor will be applied to total development costs depending on the development status of the feature [illegible] considered - The factor will range from [illegible] A factor of [illegible] will be applied for conventional applications and [illegible] for novel applications [illegible] - Values between these [illegible] will need to be based on [illegible] assessment of risks	Risk Factor		I II III		
[illegible]	[illegible]	Total Development [illegible]			I II III		

INVESTMENT COST

[illegible] No.	Cost Element	Content & Function	Factors: Variable	Factors: Default	[illegible]	[illegible]	[illegible]
	Price per Aircraft						
[illegible]	- Share of [illegible] cost per A/C	≙ [illegible] [illegible] A/C	[illegible]	[illegible]	[illegible]		
[illegible]	[illegible] Equipment	- Based [illegible] equipment [illegible] [illegible] ≙ [illegible] / [illegible] / [illegible]	[illegible]	[illegible]	[illegible]		
[illegible]	Material [illegible]	- Material [illegible] Standard parts [illegible] parts [illegible] ≙ Material [illegible] / [illegible]	[illegible]	[illegible]	[illegible]		
[illegible]	[illegible]	[illegible] A/C [illegible] [illegible] ≙ [illegible] / [illegible] [illegible] / [illegible]	[illegible]	[illegible]			
[illegible]	[illegible]	[illegible] [illegible] ≙ [illegible] / [illegible]	[illegible]	[illegible]			

Step No.	Cost Element	Content & Function	Factors: Variable		Factors: Constant	[illegible]	To be calculated down to level of: System Sub-system	Unit Component
22	- Aircraft Cost per Fleet	Σ Cost per A/C x required Qty of A/C's	Cost per A/C	Required Qty of A/C's				
			- - - - - -			I	- - -	
			- - - - - -			II	-	
			- - - - - -			III	- -	
	Support Equipment							
23	- Ramp Tester Shop Tester	o based on the GSE and tooling list per system	Cost per Type	Qty per Fleet	Burden Factor			
24	- Special Tooling	f ≙ Cost per Type / Req. Qty per Fleet / Burden Factor	- - - - - -			I	- - - - - -	
			- - - - - -			II	- - -	
			- - - - - -			III	- -	
	Spares, Basis Provisioning							
25	- A/C Equipment	o based on the equipment list per system required Qty per unit type f ≙ Rotation Time per Unit Type / Qty of Units per Type per Fleet / A/C Utilisation per Year / Removal Rate / Relation between Removal and Defect / Cost Req. Qty per Unit Type / Cost per Unit / Burden Factor	Rotat. Time per Unit Type Remov. Rate	Qty of Units per Type per Fleet / A/C Utili-sation per Year Relat. between Removal and Defect / Cost per Unit	Burden Factor			
			- - - - - -			I	Σ	
			- - - - - -			II	Σ	
			- - - - - -			III	Σ	
26	- A/C Manufacturer Parts	not considered if no large differences between the alternatives exist						

Step No.	Cost Element	Content & Function	Factors: Variable	Factors: Constant	[illegible]	To be calculated down to level of: System Sub-system	Unit Component
	Initial Training						
27	- Flight Crew	f ≙ % from step 9, documentation	Result step [illegible]	%			
					I		
28	Line & Shop [illegible]				II		
					III		
29	Σ Step [illegible] - 28	Total Investment Cost per Fleet			I		
					II		
					III		

OPERATION COST to be calculated per A/C system per year

Step No.	Cost Element	[illegible]	[illegible]
[illegible]	Cost for Fuel / Cost Penalty for Higher Fuel Consumption [illegible] / Differences in: weight, drag, engine [illegible], [illegible], operational techniques	[illegible]	[illegible]
[illegible]	[illegible] Maintenance	[illegible]	[illegible]

FIG. [illegible]

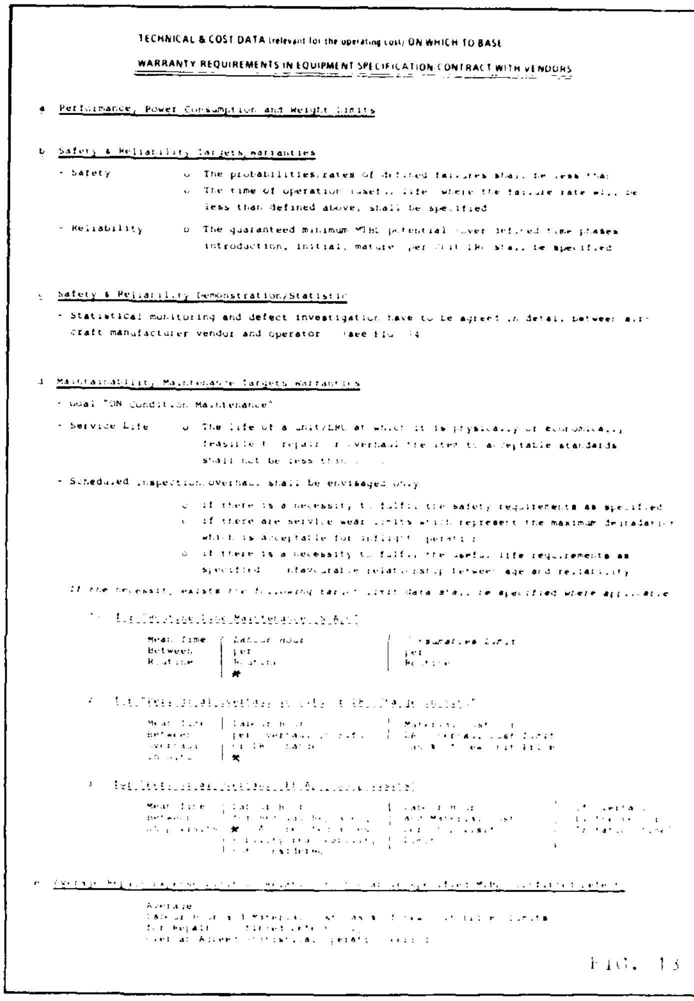
3. TECHNICAL AND COST DATA RELEVANT FOR THE OPERATION COSTS ON WHICH TO BASE WARRANTY REQUIREMENTS IN EQUIPMENT SPECIFICATIONS/CONTRACTS WITH SUPPLIERS

3.1 If a decision has been reached in favour of a system design on the basis of the determination of cost described above, the data and values on which the decision was based must be realized and ensured.

Amongst other things, this means that the subsystem/equipment data associated especially with the operating costs must be laid down as guaranteed values in specifications/contracts with the suppliers.

3.2 The major items in this connection are outlined as follows in FIG. 13:

- o Performance, consumptions, weight
- o Safety and reliability requirements
- o Scheduled maintenance expenditure limits
- o Average repair expense limit
- o furthermore, a procedure providing statistical monitoring of the above mentioned guarenteed values/ data by the contract participants, i.e. "aircraft manufacturer, operator, equipment supplier" must be agreed in the terms of the contract, in order to justify the warranty claims.



TECHNICAL & COST DATA (relevant for the operating cost) ON WHICH TO BASE

WARRANTY REQUIREMENTS IN EQUIPMENT SPECIFICATION CONTRACT WITH VENDORS

a Performance, Power Consumption and Weight Limits

b Safety & Reliability Targets/Warranties

- Safety — o The probabilities/rates of defined failures shall be less than
  o The time of operation (useful life) where the failure rate will be less than defined above, shall be specified
- Reliability — o The guaranteed minimum MTBF potential (over defined time phases introduction, initial, mature) per unit LRU shall be specified

c Safety & Reliability Demonstration/Statistic

- Statistical monitoring and defect investigation have to be agreed in detail between aircraft manufacturer vendor and operator (see FIG. 14)

d Maintainability, Maintenance Targets/Warranties

- Goal "ON Condition Maintenance"
- Service Life — o The life of a unit/LRU at which it is physically or economically feasible to repair or overhaul the item to acceptable standards shall not be less than
- Scheduled inspection/overhaul shall be envisaged only
  o if there is a necessity to fulfil the safety requirements as specified
  o if there are service wear limits which represent the maximum degradation which is acceptable for sufficient operation
  o if there is a necessity to fulfil the useful life requirements as specified (favourable relationship between age and reliability)

FIG. 13

4. PERMANENT COMPARISON OF TARGET DATA WITH ACTUAL DATA DURING A/C OPERATION TO DETERMINE DEVIATIONS OF PLANNED BUDGETED OPERATING COSTS

4.1 A vital, important tool for realizing the precalculated and budgeted operating costs is a permanent statistical comparison between the target values and the actual technical data as well as the actual cost data.

Reference has already been made to such an agreed monitoring procedure between aircraft manufacturer/operator/equipment supplier in paragraph 3.2 above.

Necessary actions/modifications can only be recognized and initiated early on the strength of such a procedure in order to reduce negative deviations from budgeted costs.

4.2 FIG. 14 gives a rough outline of the major criteria in terms of the dunctional flow of such a procedure, in view of the fact that a more detailed elaboration of this would exceed the scope of this paper.

Nevertheless in view of the importance of this subject and the various parties involved this could be worth a separate symposium.

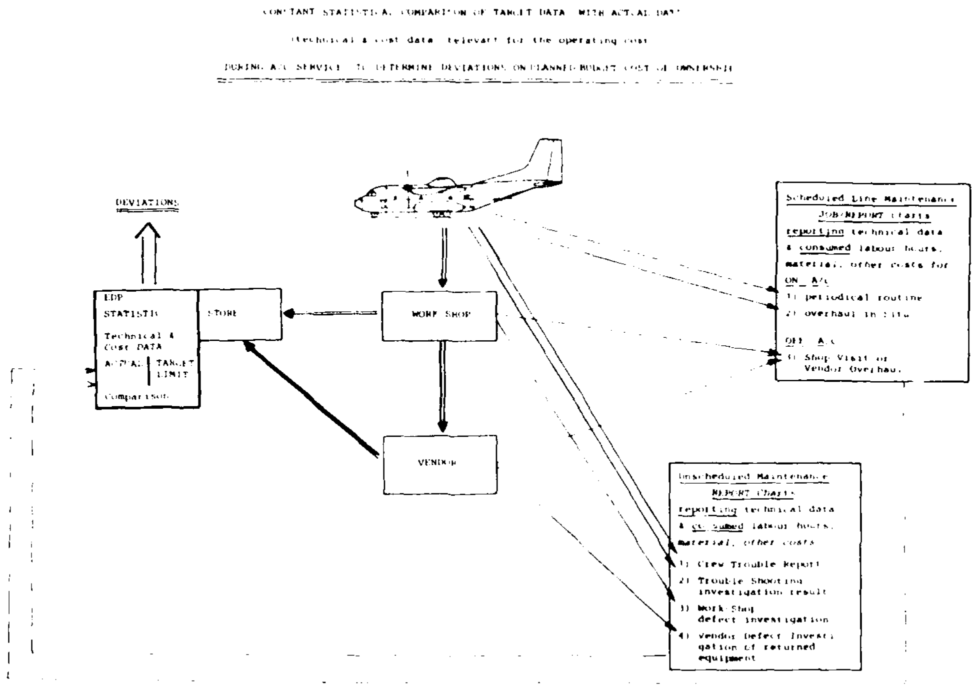


FIG. 14

5. CONCLUSIONS

A genuine "DESIGN TO COST" is only possible if the following procedures have been prepared in detail and agreed between all parties concerned:

- determination of total cost
- specification of guaranteed values
- statistical monitoring in the utilization phase.

A further point to note is that the partners involved must be prepared to bear the considerable increase in terms of cost and time during the definition/project phase.

6. REFERENCES

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2. Lankenau, H. — "Abriß der bei der Transporter-Konzeptfindung angewendeten Kostenverfahren" VFW-Fokker/DGLR 79-054, 17. Mai 1979

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MISE EN OEUVRE DES CONCEPTS DE REDUCTION DES COUTS CHEZ MESSIER-HISPANO-BUGATTI

par

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RESUME

Dans une première partie, l'Auteur rappelle les caractéristiques des produits de MESSIER-HISPANO-BUGATTI vis à vis des problèmes de réduction des coûts, précise les quatre concepts utilisés par M-H-B dans ce domaine (industrialisation, analyse de la valeur, conception à coût de production objectif, conception à coût de vie objectif) et indique les moyens nécessaires à la mise en oeuvre de ces concepts.

L'Auteur détaille ensuite les conditions et les résultats d'utilisation de ces quatre concepts à M-H-B et conclut en dressant un bilan de ces actions.

La Société MESSIER-HISPANO-BUGATTI développe les actions de réduction des coûts depuis 1969. Mon propos est de vous exposer la mise en oeuvre des concepts de réduction des coûts et les résultats obtenus. Nous suivons le plan suivant - Planche 1.

1. LA PRODUCTION M-H-B ET SES PARTICULARITES - Planche 2

1.1 M-H-B conçoit et produit des trains d'atterrissage, des équipements hydrauliques, des roues et freins.

1.2 L'ensemble de ses productions représente environ 3000 ensembles différents.

Le nombre de références de pièces (y compris les POE*) constituant ces ensembles est de l'ordre de 50 000.

Les temps d'usinage varient de quelques centièmes d'heure pour atteindre un maximum de 500 heures, le temps moyen par pièce étant de 1 à 2 heures.

Les quantités de pièces par lancement sont de l'ordre de :

200 pour les petites pièces
30 pour les pièces moyennes
10 pour les pièces importantes

Les cycles de production s'échelonnent de 5 à 24 mois suivant l'importance des pièces (approvisionnement et fabrication).

C'est donc une production :

très diversifiée
à longs cycles
à petite cadence

1.3 La répartition des coûts entre la main-d'oeuvre d'une part, la matière et les POE d'autre part, est variable suivant les types de matériels, voir planche 3.

Dans les trains d'atterrissage, la part matière et POE varie suivant qu'il s'agit d'un avion de combat ou d'un avion civil de 15 à 40 %.

En hydraulique, la part matière et POE est de l'ordre de 15 %.

Pour les roues, elle est de l'ordre de 50 % et pour les freins, elle avoisine [illegible] %.

Cela signifie que les actions de réductions des coûts ne doivent pas se limiter à la main-d'oeuvre, mais aussi à la part matière et POE.

1.4 Comment sont organisées les actions de réduction des coûts, voir planche 4.

Sous l'autorité de la Direction Technique, se situe un département dont je suis le responsable ; département à vocation de méthodes générales, chargé de la réduction des coûts et des devis.

Dès l'origine d'un projet, nous intervenons sur les coûts en agissant sur la conception, les moyens à mettre en oeuvre et sur les approvisionnements.

* POE : Produits Ouvrés Extérieurs : BOI : Bought Out Items

2. RAPPELONS RAPIDEMENT LES QUATRE CONCEPTS DE REDUCTION DES COUTS

Nous les citons dans l'ordre chronologique de leur application chez M-H-B :

2.1 Industrialisation - Planche 5

A partir de spécifications et d'une conception qui, dans la plupart des cas, ne sont pas remises en cause, la Direction Technique élabore un projet. Ce projet fait l'objet de deux actions :

1) Un premier devis

2) Une industrialisation qui consiste à rechercher les simplifications et optimisations sur les plans de la construction, des approvisionnements, des dessins, et des gammes de fabrication.

A l'issue de cette industrialisation, de nouveau deux actions :

1) 2ème devis qui permet d'estimer les gains de l'industrialisation

2) Etablissement des liasses de fabrication par les bureaux d'études

A noter (voir planche 6) que le gain est d'autant plus important que l'action d'industrialisation est introduite le plus en amont de la conception.

2.2 L'analyse de la valeur - Planche 7

Une des différences essentielles entre l'industrialisation et l'analyse de la valeur consiste à établir un histogramme du coût des fonctions.
L'histogramme présente une allure normale comme sur la partie haute de la planche. L'action de la réduction des coûts consiste par analyse fine à diminuer les coûts par fonctions.

L'histogramme, comme sur la partie basse, présente un classement anormal des coûts.
Il faut remettre en cause la conception et par créativité, élaborer une nouvelle conception donnant un histogramme correct.

2.3 La conception à coût de production objectif (C.C.O.) - (D.T.C.)

C'est une méthode de gestion de programme pour guider la conception dans le but prioritaire d'assurer un coût objectif (voir planche 8).

Nous trouvons en plus des spécifications techniques, un coût objectif C.

Ce coût objectif est d'abord vérifié par calcul de coût paramétré.

Deux cas peuvent se présenter après calcul :

1er cas

Le coût C1 est du même ordre que le coût C objectif.
La réduction de coût se fait à partir d'un projet par industrialisation et analyse de la valeur.

2ème cas

Le calcul de coût paramétré donne une valeur C'1 supérieure au coût objectif C.
Les spécifications sont remises en cause afin d'assurer le coût objectif, où l'on admet un taux de change (coût/performance).
En plus (voir planche 9), ce coût est contrôlé à toutes les grandes étapes de développement du produit.

2.4 La conception à coût de vie objectif - Planche 10 (D.T.L.C.C.)

Comme dans la conception à coût de production objectif, c'est le coût qui est prioritaire, mais non plus au niveau de la production, mais au niveau de l'ensemble des dépenses (développement, outillage, production, utilisation, maintenance).

3. LES MOYENS NECESSAIRES - Planche 11

Si l'on veut mener à bien les études de réduction des coûts, il faut disposer de moyens performants d'estimation des coûts en main-d'oeuvre et en approvisionnement.

Ces moyens doivent être actualisés, rapides et fiables.

Actualisés par la connaissance des moyens de production et de leur incidence sur la conception et les coûts.

Rapides et fiables

Dans le cas de calculs classiques, il faut posséder des abaques, des méthodes et des synthèses de calculs de coûts.

Dans le cas de calculs paramétrés, le coût doit pouvoir être exprimé en fonction de deux paramètres techniques et de deux paramètres de production.

Tous ces calculs doivent être vérifiés par les réalisations.

Nous insistons particulièrement sur la nécessité de posséder ces moyens qui sont pour nous une des clefs de la réussite.

EXAMINONS MAINTENANT LA MISE EN OEUVRE ET LES RESULTATS DE CHAQUE CONCEPT

4. L'INDUSTRIALISATION - Planches 12 et 13

Pour nous, l'industrialisation présente quatre domaines d'activités différentes :

4.1 L'orientation des moyens, par exemple :

Evolution des dessins en fonction de l'emploi de machines à commande numérique.

Avantages de l'emploi d'une presse de 65 000 t sur les plans :

Performances et coûts

Etude d'une unité de production de frein

Simplification de la fabrication de patins de frein en liaison avec le fournisseur (optimisation de la gamme).

4.2 Amélioration de la technoligie industrielle

Concerne essentiellement l'harmonisation et l'optimisation des gammes de fabrication avec les trois usines de notre groupe.

4.3 Etablissement des devis industriels

Nous estimons que ces trois activités sont indispensables si l'on veut appliquer et développer les concepts de réduction des coûts.

4.4 Industrialisation des matériels

C'est la recherche avec le bureau d'étude et avec l'assistance des services de production des solutions les plus économiques.
L'industrialisation se fait à deux stades : au stade du projet ou au stade de la production, exemple :

Projet : att. AIRBUS - Pompes hydrauliques

Production : att. MIRAGE F1 - Frein AIRBUS - Electro-distributeur

Les résultats de l'industrialisation sont d'autant plus importants qu'ils sont menés en amont des études.

4.5 Résultats de l'industrialisation en utilisant le ratio : R

$$R = \frac{\text{GAIN SUR 2 ANS - DEPENSES D'OUTILLAGES}}{\text{DEPENSES D'ETUDES}}$$

Ce ratio R se situe aux environs de 14. Il est supérieur à 14 si l'on intervient au stade du projet et inférieur à 14 si l'on intervient en production.

En général, l'industrialisation amène :

Une baisse de coût de production de l'ordre de 12 %

Une augmentation des pièces standards dont la valeur passe sur certains matériels hydrauliques de 19 à 57 %

Des synthèses technologiques pour la conception

5. L'ANALYSE DE LA VALEUR - Planche 14

5.1 Les points nécessaires à l'implantation de l'analyse de la valeur sont :

Résultats positifs de l'industrialisation

Rattachement du département de réduction de coût à la Direction Technique

Bonne collaboration avec les usines

Possession de méthodes performantes de calculs des coûts

Formation au travail en groupe

5.2 Réduction des coûts par utilisation de l'analyse de la valeur

En "Value Analysis" :

Ces analyses permettent de procéder à des transferts, des synthèses et des recherches de nouvelles solutions, exemple, commande d'orientation train avant.

En "Value Engineering" :

Analyse des fonctions, histogramme des coûts, recherche des solutions éliminant les fonctions inutiles et réduisant le coût des fonctions principales.

Exemple : frein carbone MIRAGE 2000

5.3 Résultats de l'analyse de la valeur

En utilisant le même ratio R (voir planche 14), on constate que les résultats sont plus performants qu'en industrialisation.

6. CONCEPTION A COUT DE PRODUCTION OBJECTIF - Planche 15

Détermination de l'objectif :

Cette détermination impose :

Une parfaite définition des spécifications techniques et de production.

Une confiance entre clients et fournisseurs.

Une définition de taux de transaction (coût/performances)

Une évaluation des coûts par méthodes paramétrées

La projection 15 indique pour des matériels différents, les paramètres techniques et de production utilisés.
Il faut disposer par type de matériels d'un nombre important de devis dont les valeurs sont contrôlées et homogènes.

On écrit l'équation des coûts et par régression logarithmique, on recherche la valeur des coefficients rendant minimum les écarts entre les devis et l'équation.

Méthodologie

On utilise la même méthodologie qu'en industrialisation et qu'en analyse de la valeur.
Toutes les solutions sont à chiffrer rapidement d'où moyens de calculs performants.
En plus, le coût objectif est contrôlé à tous les stades : conception, gamme et réalisation.

Résultats - Planche 16

Le tableau de la planche 16 donne les résultats obtenus.
Ils sont très significatifs et vérifiés jusqu'au stade des dessins et en partie sur les gammes et en réalisation.

7. CONCEPTION A COUT DE VIE OBJECTIF - Planche 17

Le coût de vie objectif est la somme de l'ensemble des dépenses depuis la conception jusqu'à l'utilisation et la maintenance.

Domaine d'application chez M-H-B :

Nous avons utilisé ce concept pour les freins.
L'analyse a porté essentiellement sur :

1) Le coût de production en recherchant :

La simplification maximum des dessins

L'optimisation des fonctions

L'étude des moyens à mettre en oeuvre pour la fabrication

2) Le coût d'utilisation : coût par atterrissage (CPL) Cost Per Landing :

Ce coût est pour l'utilisateur primordial.

Il est de l'ordre de 5 à 6 fois le coût d'acquisition.

Le CPL est la division de la valeur des pièces consommables par l'endurance.

Les travaux concernant la réduction du CPL ont duré plus de 5 ans et ont été menés dans un climat de confiance avec le fournisseur de patins frittés.

Les résultats apparaissent sur la planche 18.

Le coût de production passe de 1 à 0,55 et le coût d'utilisation (CPL) de 1 à 0,3.

8. RESULTATS COMPARES DE DIFFERENTS CONCEPTS DE REDUCTION DE COUTS - Planche 19

Industrialisation et analyse de la valeur :

Le tableau met en évidence la plus grande performance de l'analyse de la valeur.
A noter que l'analyse de la valeur, si elle est environ 50 % plus performante que l'industrialisation, nécessite un accroissement descoûts d'étude d'environ de 10 à 15 %.

Conception à coût de production et coût de vie objectif :

L'objectif fixé est en général atteint au stade de la conception avec des gains de l'ordre de 30 %, à vérifier en cours de production et d'utilisation.
Les différents concepts de réduction de coût amènent d'autres retombées :

Règle d'établissement des dessins

Règle d'établissement des gammes

Standardisation

9. CONCLUSIONS - Planche 20

L'utilisation de concepts de réduction de coûts de plus en plus ordonnés et systématisés a permis d'obtenir des résultats concrêts, mais ils impliquent :

Une discipline de travail

La participation de tous

Le rattachement à la Direction Technique

L'optimisation des moyens de production

La possession et l'actualisation de moyens de calculs de coûts performants.

LA MISE EN OEUVRE DES CONCEPTS DE REDUCTION DES COUTS
CHEZ M-H-B (MESSIER-HISPANO-BUGATTI)

(Planche 1)

- **Production M-H-B et réduction des coûts**
- **Les 4 concepts de la réduction des coûts**
- **Les moyens nécessaires**
- **Industrialisation**
- **Analyse de la valeur**
- **Conception à coût de production objectif**
- **Conception à coût de vie objectif**
- **Résultats des différents concepts**
- **Conclusions**

PRODUCTION M-H-B

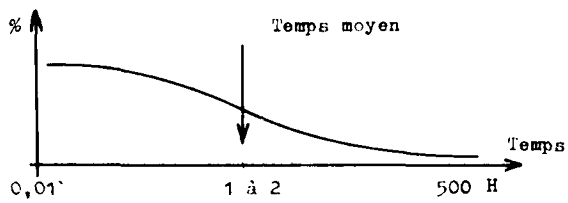
(Planche 2)

$$\underbrace{\text{Train} \quad \text{Equipement hydraulique} \quad \text{Roue-frein}}$$

Nombre d'ensembles : ~ 3 000

Nombre de pièces : ~ 50 000

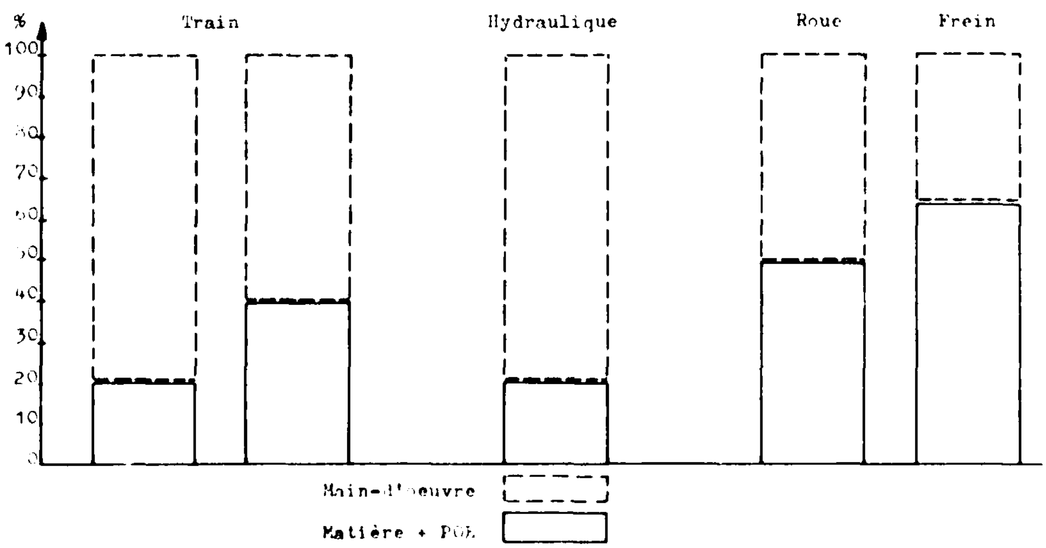
Temps d'usinage :



Quantités de lancement :	200	30	24
Cycles (mois) :	5	10	24

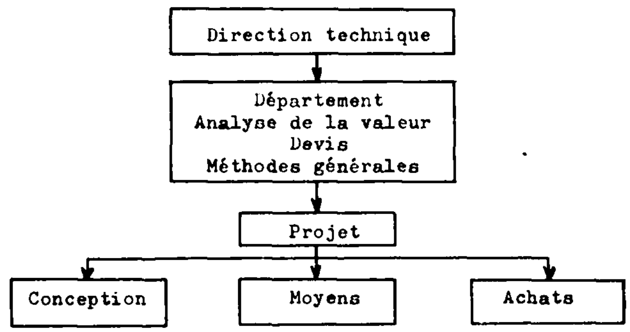
REPARTITION DES COUTS

(Planche 3)



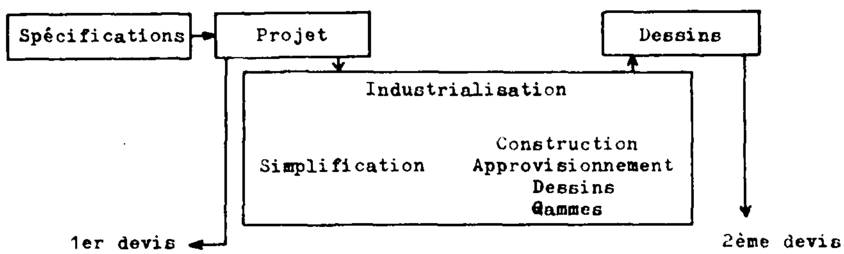
ACTIONS DE REDUCTION DES COUTS

(Planche 4)



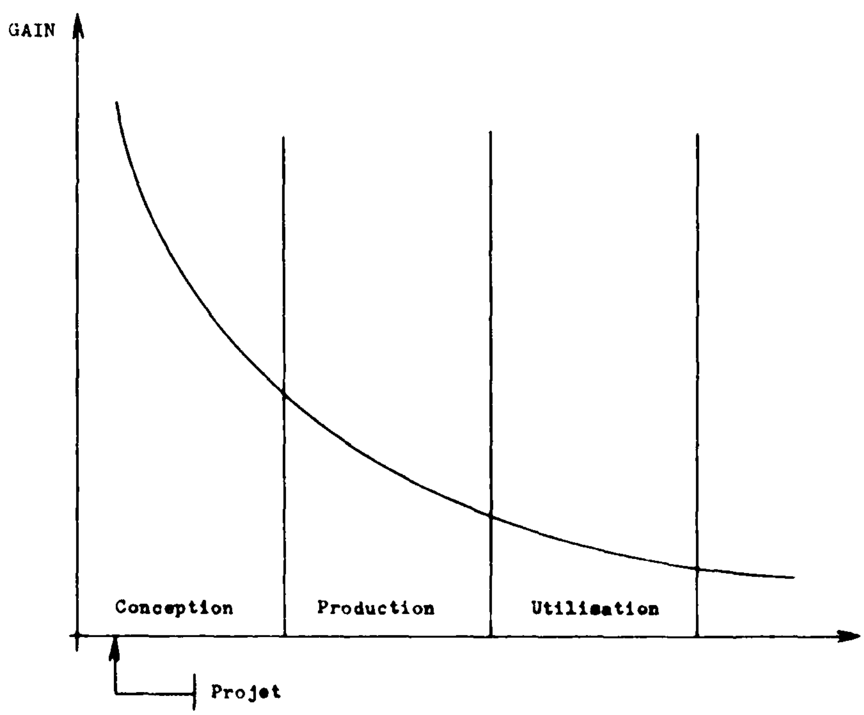
INDUSTRIALISATION

(Planche 5)



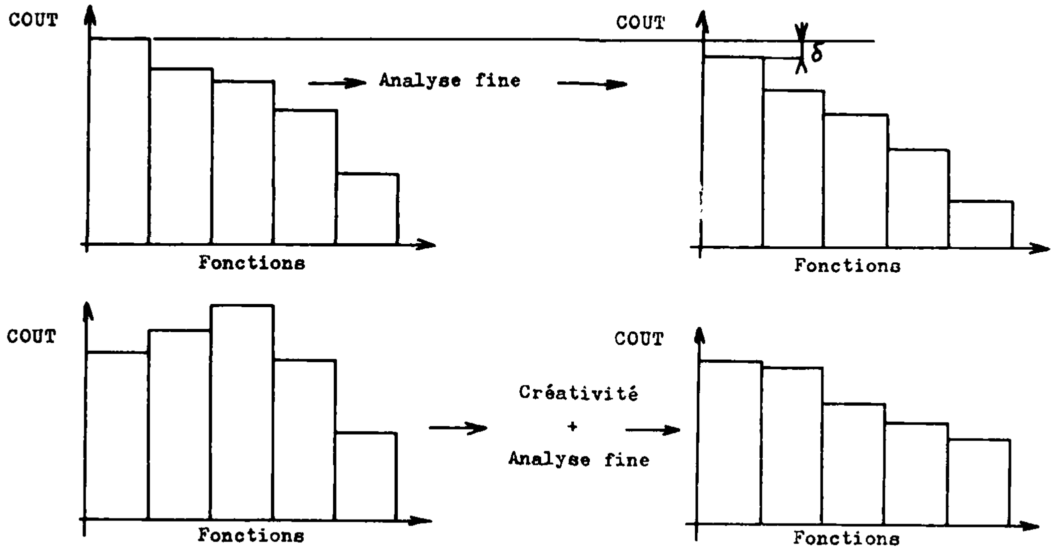
GAIN = f (STADE D'INTERVENTION)

(Planche 6)



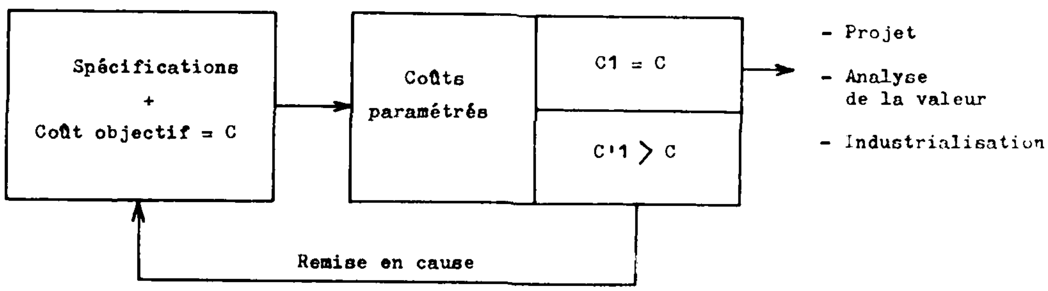
ANALYSE DE LA VALEUR

(Planche 7)



CONCEPTION A COUT DE PRODUCTION OBJECTIF (CCO)

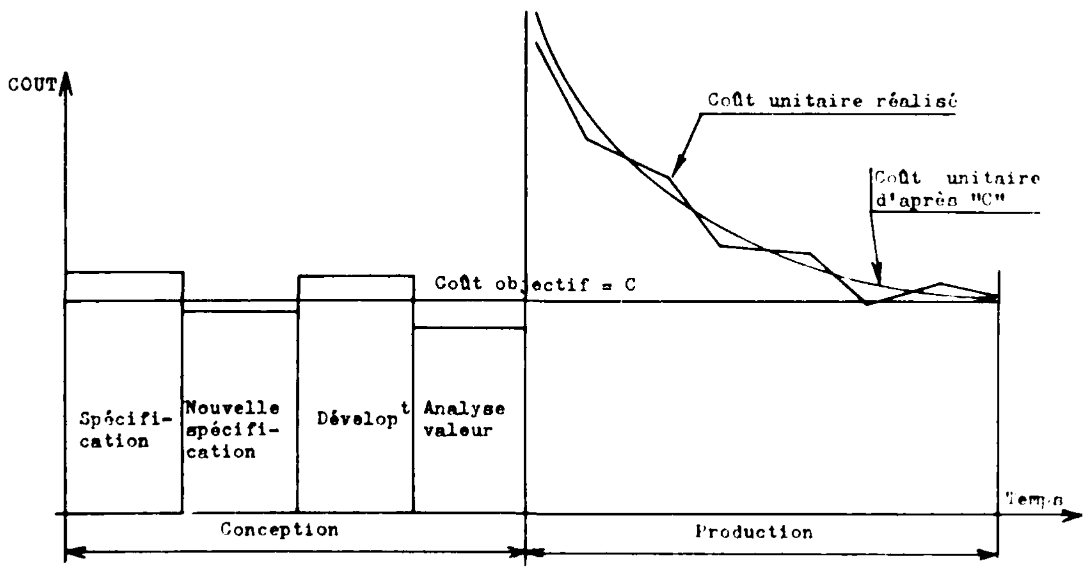
(Planche 8)



C. C. O.

CONTROLE PERMANENT DES COUTS

(Planche 9)



CONCEPTION A COUT DE VIE OBJECTIF

(Planche 10)

C.C.O. - D.T.C. → Coût de <u>production</u> objectif

D.T.L.C.C. → Coût total {
- Développement
- Outillages
- Production
- Utilisation
- Maintenance

MOYENS
(CALCUL DES COUTS)

(Planche 11)

Actualisés	Rapides	Fiables
Moyens de production	Classiques	Paramétriques
Incidences sur conception et coûts	Abaques Méthodes ↓ Main-d'oeuvre Approvisionnement	Coût = f (techniques)
<u>*TRES IMPORTANT*</u>	→ Réalisations ←	

INDUSTRIALISATION

(Planche 12)

1 - Orientation des moyens

2 - Amélioration de la technologie industrielle

3 - Etablissement des devis

1 - 2 - 3 : INDISPENSABLES

4 - Industrialisation des matériels
- Rappel
- Projet
- Production

RESULTATS

(planche 13)

RATIO = R

$$R = \frac{\text{Gain sur 2 ans - Outillages}}{\text{Etudes}}$$

$R \simeq 14$ > 14 Projet
             < 14 Production

- Coût de production = - 12 %
- Standardisation 19 % --▶ 57 %
- Synthèses technologiques pour conception

ANALYSE DE LA VALEUR

(Planche 14)

- Points nécessaires
- Développement de la réduction des coûts par analyse de la valeur
  - Value analysis
    → Orientation
  - Value engineering
- Résultats

RATIO = R

	R	GAIN
Industrialisation	14	12 %
Analyse de la valeur	22	17 %

22 → 29 Value analysis ; 22 → 10 Value Engineering

CONCEPTION A COUT DE PRODUCTION OBJECTIF

C.C.O.

(Planche 15)

- Détermination
- Evaluation des coûts: méthodes paramétriques

$P = a \ (A^{\alpha} \times B^{\beta} \times C^{\gamma} \times D^{\delta})$

P = Devis

Détermination de $a, \alpha, \beta, \gamma, \delta$ par régression exponentielle

- 4 paramètres

	Techniques	Production
Accumulateur	Volume Masse	Quantité Cadence
Frein	Energie Commande hydraulique	Quantité Cadence
Vérin	Masse Effort	Quantité Cadence

METHODOLOGIE

(Planche 16)

PERMANENCE DU CONTROLE DES COUTS

Résultats :

	Coût initial	Coût Objectif	Contrôle		
			Dessin	Gamme	Production
AS.332	1	0,65	0,67	En cours	
A.310	1	0,95	0,96	En cours	
Distributeur	1	0,7	0,72	0,71	0,69
Roue	1	0,55	0,57	0,55	0,58

CONCEPTION A COUT DE VIE OBJECTIF

C.C.V.O.

(Planche 17)

- Coût objectif = Σ (développement, outillage, production, utilisation, maintenance)
- Application chez M.H.B. : frein
- Coût de production : - Analyse de la valeur
  - Moyens à utiliser
- Coût d'utilisation : $\simeq$ 5 (coût d'acquisition)

$$C.P.L. = \frac{\text{Pièces consommables}}{\text{Endurance}}$$

C.P.L. = Cost Per Landing

RESULTATS

(Planche 18)

Coût production

1 ⟶ 0,55

Coût d'utilisation (C.P.L.)

1 ⟶ 0,3

RESULTATS COMPARES DES DIFFERENTS CONCEPTS

(Planche 19)

- Industrialisation - Analyse de la valeur

	Développement	Ratio R	Gain production
Industrialisation	1	14	12 %
Analyse de la valeur	1,15	22	17 %

- C.C.O. - C.C.V.O.

  Objectif atteint à la conception : -30 %
- Autres retombées :
  - Règles dessins-gammes
  - Standardisation

CONCLUSIONS

(Planche 20)

- Démonstration de la rentabilité des concepts de réduction de coût
- Points nécessaires :
  - Confiance
  - Discipline
  - Participation
  - Rattachement à la Direction Technique
  - Optimisation des moyens
  - MOYENS PERFORMANTS D'EVALUATION DES COUTS

SUMMARY OF AGARD LECTURE SERIES 100
METHODOLOGY FOR CONTROL OF LIFE CYCLE COSTS FOR AVIONICS SYSTEMS

Irving J. Gabelman
Technical Associates
Rome, New York

SUMMARY

The continually increasing costs of avionics and weapon systems during acquisition and their life-time operation is a matter of grave concern to the NATO family of nations. The NATO governments need greater visibility over these life cycle costs. Fortunately there have been formulated disciplined methods of providing such visibility and control. The Avionics Panel of AGARD, in an effort to make these methods more widely available, sponsored Lecture Series 100 on "Methodology for Control of Life Cycle Costs for Avionics Systems". The lecture series was implemented through the Consultant and Exchange Program in May 1979. This paper summarizes the presentations given.

1. INTRODUCTION

This paper will summarize the AGARD L.S. 100 on "Methodology for Control of Life Cycle Costs for Avionics Systems". The lecture series was given in Bonn, Germany on 7-8 May 1979 and then in Athens, Greece on 10-11 May 1979 by the following personnel:

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Dr. I.J. Gabelman
Technical Associates
225 Dale Road
Rome, New York 13440, USA

Lecturers

Dr. E.N. Dodson
General Research Corporation
5383 Hollister Avenue
P.O. Box 3587
Santa Barbara, California 93105, USA

Mr. T. Kiang
Bell Northern Research Ltd
P.O. Box 3511, Station "C"
Ottawa, Canada K1Y4H7

Mr. J. Klion
RADC/RBRT
Rome Air Development Center
Griffiss Air Force Base
New York, New York 13441 USA

Mr. P.G. Reich
DTI/R and ISG Mo (P.E.)
Room 7U
111 Lacon House
Theobalds Road
London WC1X8RY UK

Each of the lecturers spoke for approximately three hours. In the brief time available today only the highlights of their papers can be presented. The complete papers are available in the proceedings of the lecture series, which may be obtained through your national distribution center. The proceedings contain an extensive bibliography on various aspects of Life Cycle Costs prepared by the Scientific and Technical Information Branch of NASA.

1.1 Elements of Life Cycle Costs

Advanced technology has made available to the NATO military commander an array of highly sophisticated, extremely complex systems which help him to reach his operational objectives. Acquiring this increased capability however has been costly, so costly that it presents a significant budgetary problem to the member nations of NATO. The Life Cycle Costs (LCC), defined as the total costs of acquiring, operating and supporting a system over its lifetime, has come under careful scrutiny. Methodology has been evolved which enables costs of current weapon systems to be reduced and costs of weapons systems now in development to be controlled.

The most visible costs are those associated with procurement, research and development, test and evaluation. These account for perhaps one-third of the total LCC. Operation and maintenance, and manpower costs are roughly the other two-thirds. LCC can be lowered by limiting performance objectives; using commercial products; improving reliability; improving quality control and testing procedures and using simple designs.

The lecture series speakers described several methodologies which enable reduction in the costs of current systems and which can be used to control the LCC of systems now in development.

2. SUMMARY OF "LIFE CYCLE COST CONCEPTS" - E.N. Dodson

Life Cycle Cost (LCC) analysis is discussed in the context of several management objectives, including (1) evaluation of alternative system concepts and designs, (2) development of goals for design-to-cost programs, (3) budgetary planning for selected systems, and (4) control of costs for ongoing system acquisition programs.

The two basic approaches to LCC analysis are the industrial engineering and the parametric, or "statistical" approach. Dodson's lecture emphasizes the latter, although examples and an evaluation of the industrial engineering approach are also given.

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DESIGN TO COST AND LIFE CYCLE COST.(U)
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The parametric method is well suited to estimating life cycle costs when employed in the early stages of a programs "Life Cycle". In these early phases comparatively few details about the eventual equipments are known, yet many of the important program decisions must be made. The parametric method is based on relationships between more aggregated components of system cost and the physical and/or performance characteristics of the system. These relationships should be derived from cost histories on prior programs following the principles of statistical inference. For most new systems, the parametric approach is the only method that can be used to make an estimate from the limited information available during concept formulation, i.e., when only mission and performance envelopes are defined. Only subsequently when detailed contractor proposals are being prepared can the industrial engineering procedures be applied. Furthermore, parametric methods provide the analyst with an inexpensive means of examining the impact on cost of a variety of changes in system performance requirements - information on particular importance during the early phases of the development and planning processes.

2.1 Parametric Cost Analysis

The lecture describes the basic elements and methods of parametric cost analysis. While there are clearly defined steps, it is emphasized that the overall process is iterative. The steps given are:

1. Statement of Objectives - As in any analysis there must be a clear statement of objectives such as 1) comparison and evaluation of costs vs benefits, 2) establishment of budgets, 3) comparing costs with competing alternatives.

2. Cost Chart of Accounts - The next step is to develop a formally structured table of cost elements to be examined. One way to structure the cost chart is by means of a two dimensional array, one axis of which defines the end items such as laser optics while the second lists various elements of the system life cycle such as initial tooling.

3. Formulation of Cost Hypotheses - This includes the hypothesizing of basic estimating equations in which cost is the dependent variable and selected performance, design, or program characteristics serve as independent variables. Various mathematical forms for these equations are discussed, together with the requirements for the underlying engineering rationale to support the estimating equations.

4. Collection and Normalization of Relevant Historical Data - Data sources are discussed, together with the several procedures required to ensure that data from various sources are consistely-defined and comparable.

5. The Use of Statistical Techniques. The developing and validating of specified mathematical equations for estimating costs is discussed. There is also given steps that can be pursued if no valid estimating relationships are established.

The lectures also consider methodological refinements to LCC analysis. These include methods of measuring technological change and incorporating the effects of these changes in life-cycle cost analysis. These procedures are especially pertinent to electronics and avionics systems (which -- more than any other type of equipment -- are characterized by rapid technological change).

Throughout the discussions of life-cycle costing, procedures and the extensions involving changing technology, specific examples of avionics hardware and software are given. Software poses a number of unique problems which are discussed. These examples are drawn from the author's work for the National Aeronautics and Space Administration and other agencies, and from other published work.

In addition to the use of these procedures in life-cycle cost analysis, the lecture illustrates their use in evaluating risks associated with development and production of avionics equipment.

Also considered are the unique requirements associated with design-to-cost programs. Experience with several ongoing programs is given, together with the outlook for future developments in design-to-cost procedures.

3. SUMMARY OF "THE DEVELOPMENT AND IMPLEMENTATION OF LIFE CYCLE COST METHODOLOGY" by T. D. Kiang

3.1 Introduction

Bell-Northern Research (BNR) has developed a life cycle cost (LCC) methodology suitable for Canadian forces environments. For this methodology, a model has been developed which has the capability of relating system LCC to its availability. The LCC of a system is defined as the sum total of all present and future costs incurred in acquisition, operating and maintaining the system. Availability is defined as the probability that at any point in time the system is operating satisfactorily.

The model is computerized and tied into the field data collected under the maintenance management information systems for the Canadian forces operational environments. It is very comprehensive containing some 59 functional modules. The methodology was developed primarily to meet the needs of the Canadian Department of National Defence (DND). By standardizing on this methodology, DND obtains a common starting point for LCC evaluations. The methodology could be extended to non-DND applications to conduct LCC and availability analyses on complex systems such as power distribution, transportation and communication networks. The methodology can also be adapted to specific requirements for sensitivity analyses, evaluation of reliability improvement warranties, engineering economy studies, and other applications.

3.2 LCC Methodology

The methodology by BNR is unique in that the model relates LCC and availability in quantitative terms. The DND LCC model will maximize system availability for a given cost constraint, or minimize LCC for a given availability requirement. The model is designed to carry out comparative studies for decision-making at various stages of system life.

Due to the non-linear and complex relationship between availability and LCC, a marginal allocation approach was used. To facilitate the computation, the mathematical expressions were programmed in

Fortran IV using an IBM 370/168 virtual machine. The interactive feature of the computerized model permits rapid access to modify input data to carry out sensitivity analyses, and gives the user rapid results.

3.4 Conclusions

The study successfully demonstrates the application of the DND LCC model to the Canadian forces operating environments. The generalized model can be applied to complex systems to perform trade-offs between LCC and availability. The analysis takes into account recurring and non-recurring costs, hardware configuration, reliability data, and variations in maintenance and logistics support. It permits rapid sensitivity to cost drivers.

The DND LCC is a useful tool for comparative studies. Because the model is generalized and modular in structure, it will find applications beyond DND wherever it is desireable to optimize LCC/availability on complex systems.

4. SUMMARY OF "RECENT EXPERIENCE IN THE DEVELOPMENT AND APPLICATION OF LCC MODELS" by Jerome Klion

The analysis and study of LCC of complex weapon systems is facilitated by the use of models. This paper 1) introduces some representative available models, 2) discusses their development, 3) points out their shortcomings and sensitivities, and 4) shows several recent applications. Information on other models may be obtained in several references given in a brief bibliography.

Acquisition cost models are discussed first. There are two general types - development cost models and production cost models. The models are developed from empirical relationships found among the relevant variables in available data. These relationships are, in many cases, found by a mathematical technique known as regression analysis. Klion's paper examines in some detail this technique and gives some examples of its application.

Reliability has a significant impact on LCC. In the development cycle, efforts are made to maximize the reliability of the developed equipment. These reliability efforts include failure analysis, design reviews, parts screening, standardization, environmental testing, etc. The General Electric Company under contract to RADC developed a model which included relationships enabling the determination and prediction of costs of reliability efforts to the reliability of the developed equipment. This model and its application to various avionic equipment developments is discussed in Klion's paper. Also discussed in detail is a similar study performed by the Hughes Aircraft Company on ground and shipboard electronic equipment. Application of the Hughes model to ten electronic systems is given. In both these studies, quantitative relationships are derived which allow prediction of reliability and reliability costs based on such variables as the total number of parts (analog and digital); predicted and specified MTBF. The relationships established allow for trade-offs among parameters so that the reliability, unit production cost, etc. can be varied and optimized in accordance with specified criteria. The methodology which was developed allows the analyst to compare the reliabilities that could be expected from various combinations of the following: different designs, growth testing programmes, levels of part quality, screening methods and burn-ins, and amount and severity of limited environmental testing. The cost methodology also allows for a comparison of the associated unit production costs.

LCC modeling includes operation and support cost models. These models are basically analytical in nature. That is, an operations, maintenance and support scenario is first developed and around this scenario, a complete cost model is developed. Some of the factors considered in the development of such models are: the quantitative effect of reliability on the number of maintenance actions and spare parts requirements; the effect of maintainability on the number of maintenance manhours required, and on the manpower required per maintenance action, the development of materiel costs, and costs per manhour, for the required maintenance activities, etc. A virtual plethora of such models have been developed in the past; one report published almost eight years ago contained 46 different models.

Another type of LCC model examines reliability as a capital investment (i.e., an expenditure of funds in the expectation of a worthwhile return). Using standard economic analysis procedures, the model allows one to compute the return in reduced maintenance costs of a system procured with the elements of a comprehensive reliability program versus the return of a system with an abbreviated reliability program. Another model was formulated to compute the cost of a comprehensive reliability program. Standard budgeting procedures were employed, including consideration of overhead, general and administrative (G&A), and profit factors.

Given the appropriate development, production, and operation and support costs for a system, one can then sum them to estimate total life cycle costs. It is obvious that, since each estimate is subject to some degree of inaccuracy or error, the total LCC will be sensitive, in different degrees, to some combination of the inherent errors. A research program, and results are described which quantifies model sensitivity and develops procedures for estimating confidence intervals for LCC models

The last section of the paper describes applications of LCC models in recent U.S. Air Force procurements, including some which utilized reliability improvement warranties to minimize LCC.

5. SUMMARY OF "PROBLEMS IN THE INVESTIGATION OF RELIABILITY ASSOCIATED LCC OF MILITARY AIRBORNE SYSTEMS" by Peter G. Reich

Mr. Reich's lecture dealt with "Reliability Associated Life-Cycle Costs". These costs fall into two main categories:

a. Investment Costs. These are the costs attributable to activities that pertain to achieving or improving the reliability and maintainability of systems.

b. Support Co[illegible] These are the maintenance costs incurred during the service life of the system.

Jointly these are the "R&M" costs.

R&M costs are difficult to ascertain and even more difficult to compare from system to system. They obviously can be varied in accordance with the level of operational effectiveness that is sought or permitted. Mr. Reich points out that drawing statistical inferences by a purely statistical treatment of costs in past projects is a very difficult undertaking mainly because of the many interacting factors which influence R&M and because data on these factors is not always available or complete.

Several aircraft subsystems were chosen for study of R&M costs. These included the ILS receiver, AI radar, transponders, air conditioning electrical supply, propulsion, etc.

The lecture does not give quantitative results but does discuss the method of study of these subsystems and the associated problems. The study method outlined is as follows:

a. Collection of representative samples of data on defect rates, associated maintenance activities and unit costs of the activities.

b. Collection of samples of data from which to estimate losses of operational effectiveness.

c. Estimate the life costs of maintenance associated with identified generic types of cause.

d. Estimate the losses of operational effectiveness associated with generic types of cause.

e. Highlight the most important causes of maintenance costs and of loss of operational effectiveness.

f. Conduct historical review of the project with particular reference to the cost and effectiveness of the R&M activities, and to other factors affecting in-service reliability.

g. Hypothesize (and assign costs to) additional R&M activities that might have been profitably applied at various stages of the project.

h. Estimate the R&M gains associated with these additional activities.

i. Translate these gains in R&M to savings in life maintenance costs and increased operational effectiveness.

j. Generalize the results of i to cover whole airborne weapon systems, and indicate potential returns on investment in future projects.

k. Give a paradigm for the conduct of R&M activities in future major projects, based on a to j above.

It is seen that steps a through i constitute a detailed "case study" of each sub-system, and that this involves a thorough investigation of the "background", i.e., the initial operational requirements, timescales, contractual arrangements, and revisions to specification, etc. Steps g through i concentrate on the potential for improvement (one measure of which is the achievable reduction in life-cycle costs) to guide the formulation of policies for future projects.

Mr. Reich emphasizes that R&M studies are difficult to exploit because of the 1) varying definitions of R&M, 2) differences in scheduled maintenance policies, 3) variations in type of data taken and in the methods of acquisition, 4) relatively short sampling periods compared to length of inservice life, 5) relevance of pertinent desired operational effectiveness, etc.

In the concluding sections of his lectures, Mr. Reich deals with the relationship of operational effectiveness to life cycle costs. He gives an example of a wartime effectiveness model which, for a given type of airborne weapons system, can be used to investigate sensitivities to parametric values. The system chosen consists of an aircraft and payload designed for close-support role in land battles.

6. CONCLUSIONS AND OBSERVATIONS

6.1 Background

Mr. O.C. Boileau, formerly president of Boeing Aerospace Corporation, in a speech to the National Security Industrial Organization, remarked that he had a recurrent nightmare wherein all of the aerospace engineers in the free world are being monitored by all the civil servants. The engineers are building a solid gold airplane that can fly backwards and has a price tag equal to the national debt. He went on to say that what really bothered him was that he saw variations of that nightmare during the day in real life without closing his eyes.

Mr. Boileau's statements are graphic observations of the increasing LCC of military systems. Fortunately the problem of mounting LCC was recognized. In the U.S. some fundamental examinations of the traditional methods and concepts of development, acquisition, operation and support of military systems were undertaken by the department of defense. DOD Directive 5000.28 was issued which explicitly emphasized that management of weapon systems would ensure establishment of "costs as a parameter equal in importance with the technical requirement and schedules". Three major points were made in Directive 5000.28:

1. O&S cost goals and unit acquisition costs should be specified early in the procurement cycle.

2. Specific measurable quantities such as MTBF should be established contractually and measured during the test and evaluation phase and in operation.

3. Incentives to reduce LCC should be established.

One of the principal considerations leading to DODD 5000.28 was the decline in purchasing power for new weapon acquisition due to the increasing O&S costs. Formerly little explicit attention was given to outyear support and operating costs during development. Now a decision coordinating paper (DCP) is agreed to by the DOD and the military services to ensure that the following points are considered in their weapon system procurements:

1. O&S cost visibility
2. Design trades to minimize LCC
3. Contract incentives to reduce O&S costs
4. Logistics alternatives.

This emphasis by government and industry, not only in the U.S. but also in the other members of NATO, on LCC motivated an aggregation of techniques from engineering and mathematics into a coherent discipline addressed to the task of reducing LCC - of satisfying the goals of DODD 5000.28 and the DCPs.

LS 100 was an integrated series of lectures assembled to acquaint the AGARD community with these techniques and with the results of their application. Each lecture addressed a major aspect of LCC, presenting background, definitions, principles, applications and results. These lectures have been summarized. The remainder of this paper comments on the content of each of the lectures.

6.2 Life Cycle Cost Concept - E.N. Dodson

Dodson develops methods for obtaining "Cost Estimating Relationships" (CERs). These are mathematical equations linking measurable physical attributes of a system to its cost. An extremely simple CER for attack and fighter aircraft might be

Production Cost = $230 x weight in lbs.

This CER could be amplified and improved by including other operational parameters such as speed, range, rate of climb, etc. An example of a more complex CER developed in a USAF sponsored study in which over 40 operational radar systems were evaluated relates development cost to several radar parameters as follows: *

$$\ln C = -0.784 - 0.205 \ln A + 0.165 D + 0.151 \ln P + 0.028 + 1.370 TD$$

where

C = Radar system development cost
A = Antenna aperture
D = Degree of development
P = Peak power
S = Sensitivity
SC = Number of special circuits
TD = Type of development

Dodson shows how to develop CERs by statistical parametric analysis - that is CERs are derived by statistically analyzing data on similar operating systems or subsystems and correlating cost with physical and functional parameters.

The method is well established and as Dodson points out is the only one available to the LCC analyst for most new systems.

Another method, treated superficially in the paper, is the "Industrial Engineering Approach" wherein cost categories are defined at an elemental level with each element of the system quantified. While this method allows for simulation, trade-offs and expert inputs at detailed levels, it may be difficult to implement because of unavailability of detailed data and also can be overly subjective.

There are two methods which are comparatively simple which are not included in Dodson's paper. These are:

1. Analogy - i.e., when the system being procured is essentially the same as one previously purchased. In such instances, estimation of cost would be based on simple adjustments such as for quantity and inflation.

2. Scaling, i.e., when the new system being procured is similar to one procured in the past but with some modification. The estimating factors are more complex than in the analogy method but still simple.

The last part of Dodson's paper treats the incorporation of technological advance as a factor in CERs. This is an area to which Dodson has made many original contributions. It is obviously a significant factor in LCC and one which is very difficult to quantify.

At some point in the acquisition cycle, decisions are made on design detail which become difficult to modify or change. Planning may begin however appreciably before this point in time and there is an interval which may be appreciable in which the state of the art (SOA) advances. Dodson introduces a technique in technique in which an SOA surface is generated based on historical data. CERs then include a factor which accounts for changes in the SOA surface due to technological advances.

* H. Balban, W. Schoenfeld, J. Witt, Prediction of Development Costs for Large Radar Systems, ARINC Research Corporation, RADC Technical Report TR 67-217, April 1967

6.3 Life Cycle Cost Methodology - T.D. Kiang

CERs allow for the calculation of costs for a given system or for any component thereof. In any system of appreciable complexity, such as most weapon systems, several CERs are used to compute the overall LCC. Furthermore LCC are dependent on variables whose limits are specified by considerations such as operational effectiveness. The management of system LCC involves carrying out comparative engineering studies of the many options available at different times in the life cycle. These studies are more easily conducted with the use of computer models.

The defense establishments of several of the NATO family of nations have sponsored development of such models for use in life cycle management of systems from acquisition to disposal. Mr. Kiang's paper is representative of such an application by the Department of National Defense in Canada.

Fig. 1 shows the structure of the DND model developed by Bell Northern Research Ltd. Arrows indicate important relationships between system effectiveness and LCC.

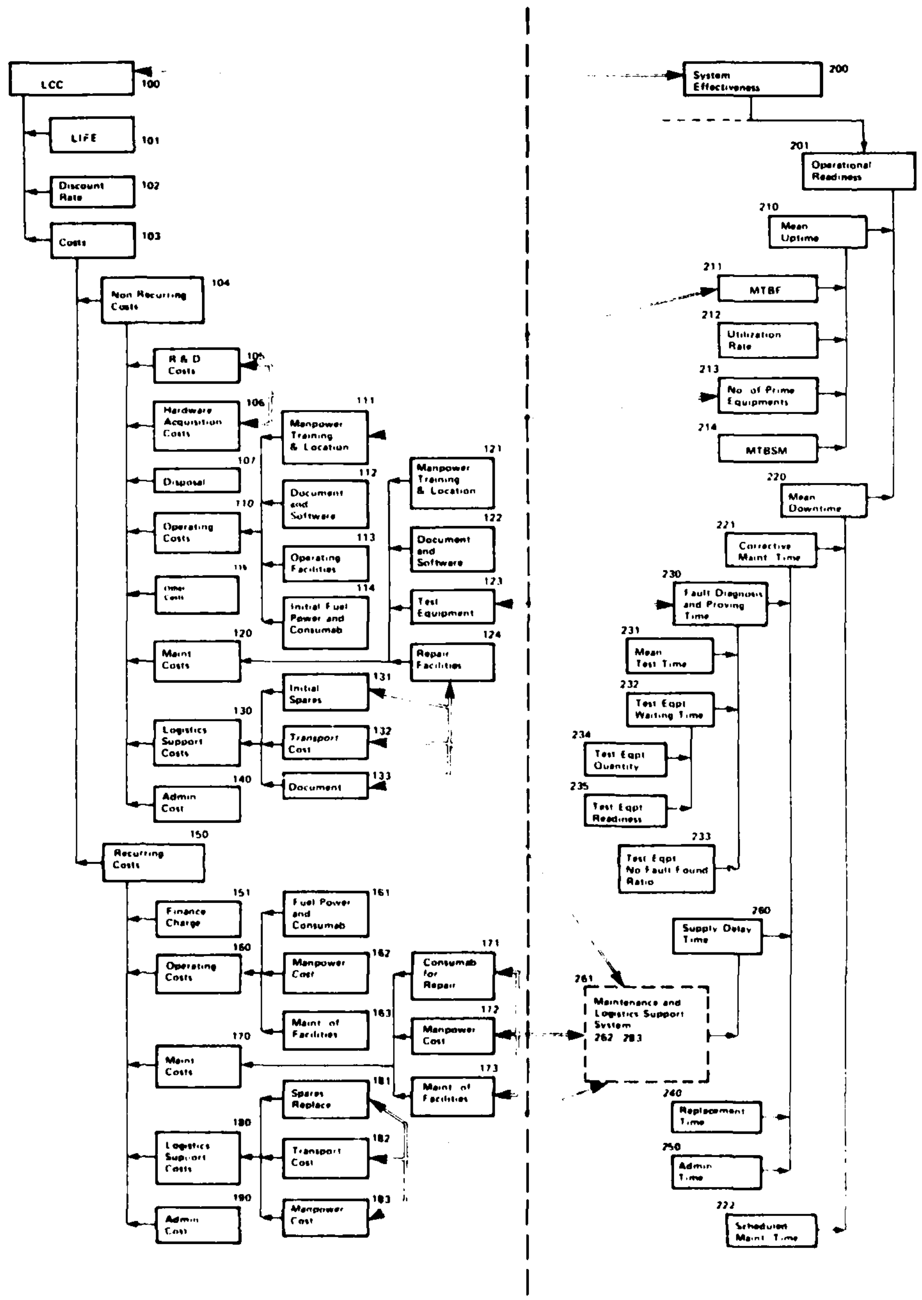

Fig. 1

Fig. 2 illustrates the many applications of the model in various stages of the life cycle.

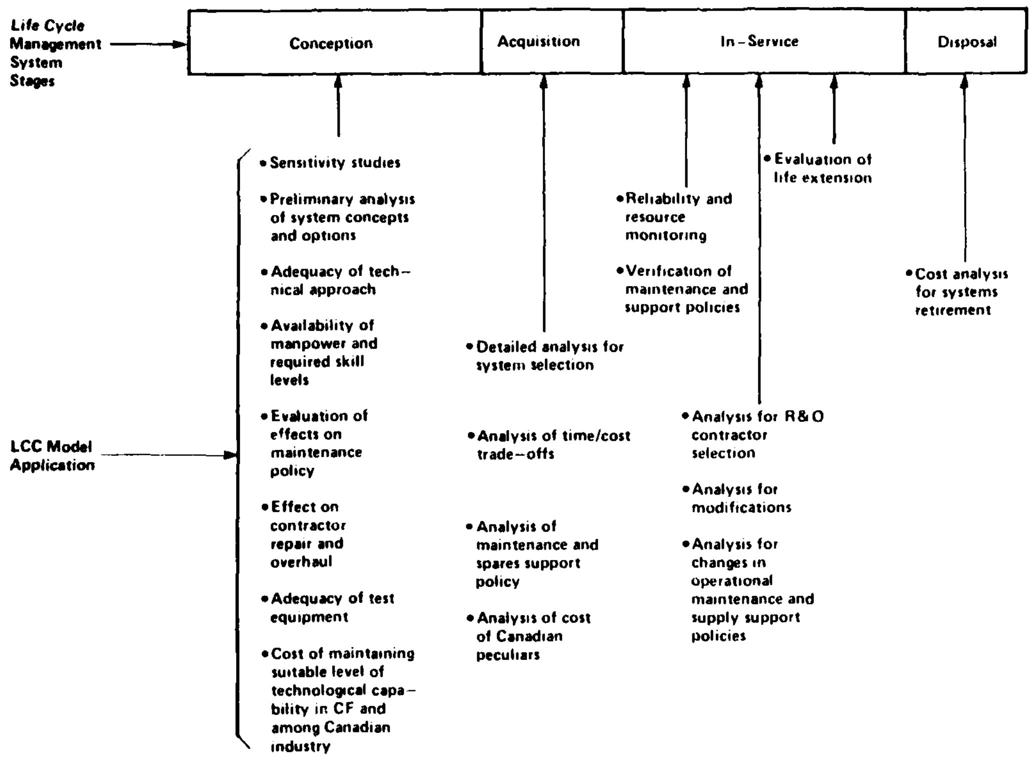

Fig. 2

The model has been used by DND in the management of several systems very successfully. Mr. Kiang details a case study on the AN/ARN 504.

6.4 Application of LCC Models - Jerome Klion

Dr. Dodson developed the concept of CERs and Mr. Kiang applied the concept in the computer model developed for DND. A successful implementation and utilization was accomplished. The development of an LCC model however is an extremely complex undertaking. Mr. Klion's paper discusses the mathematical and statistical techniques used in deriving CERs such as regression analysis. His paper for the first time in the lecture series addresses reliability as a constraint variable in LCC. LCC is highly dependent on reliability and its associated measure meantime before failure MTBF. It is intuitively apparent that as the requirement for the reliability increases that acquisition costs will increase and that O&A costs will decrease. Fig. 3 displays the classic saddle shaped curve of LCC vs MTBF for the AN/ARC-164, an aircraft communication system. Klion devotes the major portion of his paper to LCC reliability considerations. It is thorough and well documented.

RELATIONSHIPS OF QUANTITY (1000) PROCUREMENT COSTS,
LIFE CYCLE (10-YEAR) MAINTENANCE COSTS,
AND TOTAL PROGRAM COSTS TO EQUIPMENT MTBF

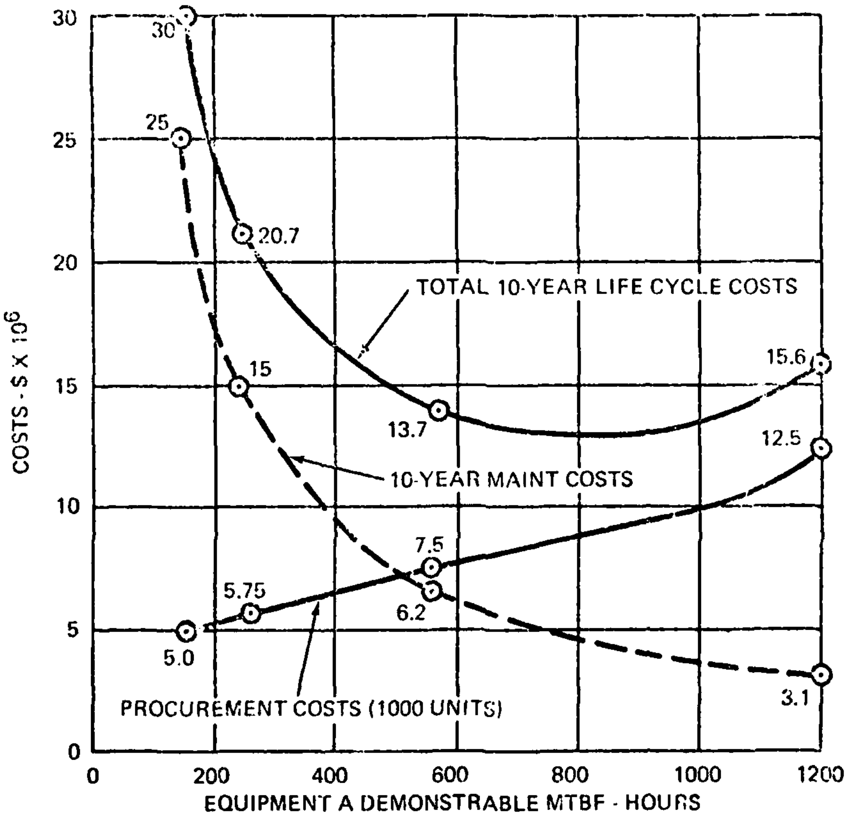

Fig.3

6.5 Problem of Reliability Associated LCC - P.G. Reich

This paper continues the emphasis of the dependence of LCC on reliability. Reich's main contribution however is his questioning of the data used in LCC forecasting. He claims that differing interpretations of reliability and maintainability lead to inaccurate specification of data to be collected and used in applicable CERs. This criticism is well taken and emphasizes the importance of understanding without ambiguity the meaning of data used. Much of the criticism directed at LCC forecasting and analysis is not really a criticism of the discipline but rather suggests that any evaluative process will suffer if the data used is faulty or used incorrectly.

DESIGN TO COST VIEWED AGAINST THE ACHIEVEMENT OF OPTIMUM SYSTEM CAPABILITY

by

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In defining the cost of a product, account must be taken of design and development, manufacture, training and training aids, support equipment such as test equipment, special tools etc., documentation, transportation and handling, operating and maintenance and finally, retirement and disposal. These can be broken down into two parts; one time costs and recurring costs. One time costs will include design and development, manufacture, training, documentation and facilities. Recurring costs normally include re-training where necessary, post design improvement studies, operating and maintenance costs and transportation and handling. These two groups are interactive in as much as poor design usually will result in heavy maintenance costs and design for the reduction of operating and maintenance costs will usually result in higher design and development costs for the achievement of the results required. There is another point in product design that must be considered as part of Assets Management, and that is the required availability or state of readiness of the equipment to perform the tasks for which it was developed. In this context, availability means, as far as the aircraft is concerned, that is must be available for despatch whenever required, irrespective of that part of the operational envelope which is to be applied. This will, of course, include deployment of aircraft as part of the operational role.

It is this latter that I would like to deal with in some depth. An aircraft can be made available to a high level of probability by having an infinite number of spares and very short fault diagnoses and repair times. One of the problems, as far as military aircraft are concerned, is that although they could have an infinite number of spares available, the probability of them being where they are required, particularly in a state of war, is remote. We must therefore consider other methods that will achieve higher levels of availability and at the same time achieve the lowest Life Cycle Cost. Among the problems to be resolved are the facts that, although things are beginning to change, the design specification usually covers the performance requirements and, to some degree at least, the reliability requirements quite thoroughly, but does not specify how the operational role of the aircraft is to be ensured under the various conditions that it could be required to operate. The Military Services probably feel that this is their business and that they have adequate techniques and facilities to handle these problems.

However, the achievement of a high level of operational readiness will not be met by the routine observation of performance, reliability and support needs alone. Their obtainment requires systematic evaluation of the design and support characteristics as part of the systems engineering process by technically qualified specialists.

This involves the interactive assessment of the impact the design will have on the technical specification of the total support requirements. The effectiveness of such an assessment and its influence on design is dependent on the meaningful application of an integrated Logistics Support concept during all phases of acquisition.

All too often systematic consideration of the solutions to the problem of total support does not begin until the system is in the production or deployment phases. While some elements of support may receive early attention, it is rare that the total support planning has a major impact on systems design. This lack of timely and systematic planning adversely affects the operational availability and cost of ownership. This really means that the design to cost should involve design to total cost. Each cost element should be clearly indicated so that those studying proposals and bid packs can see exactly what they are paying for, and slot each cost into its own budget element in such a way that different government departments can compare apples with apples when giving consideration to competitive bids. Unfortunately, the achievement of high states of readiness, fluidity of deployment, often to areas where support equipment, or labour, or facilities are not immediately available and may not be available during a particular mission, will usually be reflected in the acquisition of costs. This is because of the interaction between design for performance, reliability, maintainability and testability. To this must be added Logistics Support costs. It is felt that a highly skilled Logistics Support Engineer should not only be a part of the basic design team from the outset, but also be influential in the design review and considerations. The Logistics Support Engineer selected for this type of work should be a highly qualified and very experienced engineer, well versed in the latest technologies and capable of recommending even later technologies in the satisfaction of the total operational and logistics requirements. Logistics Support engineering must be added to the basic qualifications. Pure logistics would not, I feel, satisfy this role. This engineer must have a thorough and intimate knowledge of not only the hardware design activities, but also and probably more important, the total application to which the customer proposes to put the aircraft in both peacetime and wartime conditions, taking the worst cases into account. Among the tools available to the Logistics Support engineer would be simulation mathematical models, and by continuous interaction with the computer, he would be able to go into numerous optimisation loops to study the effects of design to-date on the required state of readiness or availability, and make design change recommendations particularly in the areas of maintainability, for the achievement of the required potential state of readiness keeping cost of ownership in mind at all times. During this process, consideration will be taken on the likely types and periods of forward deployment, labour availability and capability at the various levels of maintainability, availability

of spares, and the facilities to replace and repair faulty equipment, together with the probabilities of survival of the various equipments during the various required mission periods.

In the meantime, it would be expected that the reliability engineers would be exerting their influence on the design in the selection of components, devices and techniques to achieve the highest probability of survival during the types of missions envisaged by the aircraft user. This would include rigorous and expensive reliability testing and proving and at the same time aiming to obtain a Mean Time to First Failure which is close to the ultimate MTBF.

A number of companies such as IBM have been applying this technique for many years. As you know, IBM rent their equipment around the world, and the greatest loss leader that they could have would be high levels of equipment maintenance. They therefore spend a lot of time and money on ensuring that once a piece of hardware has been installed it will be operational as soon as possible and give minimal problems during the first phases of its operation and as little trouble as can be achieved during its life time. It is agreed that they have scheduled maintenance but at the same time, it is expected by the user, who is usually involved in his worst problems during the time while he is putting programs onto a computer and proving them, that during the early life of the computer there must be as little hardware failure or malfunction as possible. That means a high Mean Time to First Failure as a primary requirement. The achievement of Mean Time to First Failure, commensurate with the ultimate MTBF, can be both at the same time an expensive exercise and also a highly cost saving one in the long run. It will mean close interaction with the Design, Quality Assurance Organisations and Production Departments in the development and qualification of production and testing techniques.

With electronic equipment it requires very few rogue units to considerably lower the total population MTBF. Another thing is that these rogue units cause serious problems whereever they exist. The avoidance of them by extensive pre-delivery reliability testing should be an absolute necessity, but when thy do exist, their isolation must be rapid and ruthless.

This opens us a number of subjects associated with original design. Maintainability, the flexibility with regard to the possible levels at which maintenance can be performed in the interest of low cost of ownership or high levels of aircraft availability. Testability, which should produce two objectives. Firstly, the capability of equipment being tested in depth at the highest possible level. Secondly, to provide data retieval of each individual piece of equipment so that

the rate of reliability of each item in a population can be monitored. Maintainability must be flexible. Only a very short time ago, aircraft first line maintenance of its systems by anything other than removal and replacement of black boxes was unheard of. This was largely due to the technology which was available during that design era. Results obtained from built-in test equipment were limited in their application. It did isolate to a fairly high percentage faulty units, and occasionally modules within a unit, but with the advent of the so-called five day war and other short period forward base requirements, considerably more first line maintenance may be necessary, because squadrons may have to be placed in remote and sometimes cut-off areas where general spares supplies and highly qualified maintenance staff may not be available.

New technologies are increasingly able to assist in this aspect if they are included in the original design. Testability techniques can considerably assist in opening up the whole maintenance concept. In technology now becoming available, it is possible by the use of small highly efficient on-board computers, to carry out complete systems tests and display the pertinent information to the pilot, the flight engineer or the site engineer. New satellite technology would enable these results to be forwarded directly to a base computer. This computer could carry out a full fault diagnosis and display back to the aircraft the corrective action in a simple but effective form. To use this procedure effectively, the Logistics Support engineer, during the mathematical modelling techniques, would have to be very selective in the contents of the fly-away packs and the labour limitations in fitting and testing. This engineer would also have to be active in respect to the base computer programmes so as to ensure compliance with a maintenance plan optimised to suit the circumstances. The application of this form of technology will cause changes in the preparation of component maintenance manuals which would now become computerised, and probably task orientated, with very little, if any, hard copy except as a possible back-up. The days of hard copy component maintenance manuals must be becoming numbered anyway. This is because on the one hand, equipment is becoming so complex and its manuals so complicated, that they are very difficult for anyone other than a highly trained expert to understand. On the other hand, individual electronic components are becoming very reliable with the result that repetition, which aids retention after training, is becoming less and more spread out. This is making re-training a much more constant problem. Computerised manuals carrying out fault diagnoses and corrective action selection could present to the line mechanic a clearly defined maintenance task.

At second line and at depot level, it is assumed that automatic test equipment will be used for those black boxes which could not be repaired at first line and it would also be used for the sub-repairable assemblies. Programmable devices attached

to these units could store information with respect to the condition and performance of the unit. During the cycle of the unit on the automatic test equipment, information contained in the device could be discharged into a computer attached to it. This information, together with that held in the base computer, would produce a data base from which adequate monitoring of the performance and reliability of each serialised item could be achieved. With this information available, design engineers could quickly and accurately identify areas requiring post design improvement analysis and action. On the other hand it would avoid all too frequent modification embodiment to improve reliability when in fact there was no design problem. The problem could have been that of Quality Assurance handling, lack of understanding of the test procedure in the manuals, in fact anything but design.

It could be argued that the techniques that I have described would both increase cost and at the same time degrade reliability. Considering the cost first, I feel that it is only fair to say that they would increase acquisition costs. I think that this is inevitable. However, if the Life Cycle Cost is being performed concurrently with all of the other studies being carried out by the Logistics Support engineer, the ultimate cost should be reduced. This would be the object of carrying out the various optimising studies. On the other hand, if the criterion was availability, to a very high degree the cost would be higher, but still tightly controlled. However, it is felt that the aim should be to optimise performance, reliability, testability and availability to the lowest Life Cycle Cost achievable. This would require limits and tolerances to be put on these four elements in the original specification, otherwise the Logistics Support engineer cannot apply optimising techniques.

A satisfactory Life Cycle Cost analysis should reduce the quantities and hence the cost of expensive spares. It should optimise the application of test equipment and its location. It should be able to specify the grades of labour required and indicate their most satisfactory location. It should therefore substantially reduce the maintenance costs. Thus an aircraft more available at lower total life cycle cost should ensue as a result of the work causing higher acquisition costs. The optimising process should be a continual interactive exercise from the onset of development right through to the end of the life cycle. A great deal of assistance would come from the reliability data reporting from the actual service environment from an aircraft that would be available from the data base suggested earlier. It would assist not only with the isolation of problems and the solution in existing design, but would produce sound foundations for future designs, something that we lack at the present time.

With regard to reliability, anything added to a design must, by virtue of its being included in the hardware, degrade the reliability. Often a reasonable degredation of reliability can be tolerated to achieve other advantages such as higher maintainability or higher availability. Like everything else the degrading effect on reliability must be taken into account as part of the whole optimisation process. Availability over fixed periods will depend on reliability. It would therefore be a major data element in the mathematical modelling process.

The title or the term "Design to Cost" worries me because the true definition of it is elusive, and I can only look for a parallel in the domestic products industry. It is fairly easy for a company to employ a first class industrial designer who will produce a very fine looking piece of equipment, capable of performing a lot of functions, and then look for the market that can afford to pay for it. Some manufacturer's equipment, such as washing machines, are very expensive, because they have used good components, high quality techniques, the best of design, and they have set out to produce a long lifed reliable product. The others will design for a lower priced market, using lower cost components, a less costly design, and merely hope that the piece of equipment will live until the warranty runs out. I know that this is not being quite fair to all of industry, but between the two limits we have the situation where the buyer is looking firstly at the low acquisition costs and then at the performance of the functions he requires, paying high maintenance costs as he goes along. Another type of purchaser will look not only at the performance and the asthetics of the particular piece of equipment, but also for longevity and low maintenance costs. I think that the same problem exists with the Aviation Industry. If we were to look at the acquisition costs only, it is easy to design a low cost item that will perform as it is required to perform. It will not necessarily be reliable - sometimes it is extremely difficult to maintain and its support costs are very high indeed. Lack of good quality in manuals, which are part of the acquisition cost, will ensure high cost of maintenance and high wastage of expensive components. So I would like to end with the thought that I feel that we should design for total cost, indicating clearly in our proposals every element that makes up the cost, leaving the choice to the buyer to select those items that he requires to pay for, for the operation of his aircraft and his equipment.

AGARD Lecture Series No 107

The Application of Design to Cost and Life Cycle Cost to Aircraft Engines

Summary by

E J JONES

United Kingdom Ministry of Defence

Summary

All of the NATO nations are faced with a major concern for the growing cost of defence and the need to ensure that cost and performance are optimized. The requirements and related costs of weapon systems have come under close examination. The entire life cycle of a weapon system and its subsystems must be examined. Design and development must now consider not only the cost of production but also deployment, training, operational use, and support. The use of new technology and new management techniques are essential to obtaining the most for the available money.

The purpose of this Lecture Series is to examine the latest methodologies of cost/performance comparison and trade-offs for aircraft engines. Information will include data collection, analysis, modelling and estimating all development and operations costs.

1. INTRODUCTION

1.1 This paper summarises AGARD Lecture Series No 107 "The Application of Design to Cost and Life Cycle Cost to Aircraft Engines". The Lecture Series under the sponsorship of the Propulsion and Energetics Panel and the Consultant and Exchange Programme of AGARD was given on 12-13 May 1980 in Saint Louis, France and on 15-16 May 1980 in London, UK, by the following:

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1.2 In the brief time available today only the high lights of the papers may be presented. The complete papers are available in the proceedings of the lecture series, which may be obtained through your national distribution centre. The proceedings contain an extensive bibliography of methodology for Design to cost of Aircraft Engines prepared by the Scientific and Technical Information Branch of NASA.

2. Summary of "AN APPROACH TO AIRCRAFT TURBINE ENGINE LIFE-CYCLE ANALYSIS" by R Nelson.

This paper describes a methodology for life-cycle analysis of aircraft turbine engines derived from historical data. The methodology enables the weapon-system planner to acquire early visibility of cost magnitudes, proportions, and trends associated with a new engine's life cycle, and to identify "drivers" that increase cost and can have the effect of lowering capability. The procedure followed was to: develop a theoretical framework for each phase of the life cycle; collect and analyze data for each phase; develop parametric cost estimating relationships (CERs) for each phase; use the CERs in examples to ascertain behavior and obtain insights into cost magnitudes, proportions, and trends, and to identify cost-drivers and their effects; and examine commercial experience for cost data and operational and maintenance practices.

The methodology is applied at the engine subsystem and aircraft system levels for a military fighter aircraft to demonstrate that decisions about engine performance/schedule/cost must be made at the system level. Commercial considerations are also discussed, as is some limited historical experience about engine monitoring, an approach to obtaining the necessary information and procedures for performance and cost feedback to the engine designer.

The study was prompted by the fact that the costs of acquiring and owning turbine engines have escalated steadily over the years for both military and commercial users. Most of the causes are readily apparent. Demands for higher overall quality -- meaning performance, primarily, for the military -- have resulted in larger engines that produce greater thrust, run hotter, are costlier to maintain, and entail higher basic engine prices. Material costs associated with engine price have also risen rapidly in the recent past; over the long term, however, labor costs, primarily in the manufacturing sector, have risen proportionately more so.

The chief problem confronting this study, as it has confronted past researchers, is the lack of disaggregated, homogeneous, longitudinal ownership data that are specific to particular engine types, notably at the base and depot level. The collection of such data will be necessary for perfecting the methodology, which weapon-system planners can then use to calculate the costs and benefits of a proposed engine for a new aircraft in the early stages of planning and selection.

For a new military engine (acquired and owned under conditions similar to those with the previous engines constituting the data base) that will have an operational lifespan of 15 years, the findings indicate that:

Engine ownership costs are significantly larger than and different from those found in previously published studies. For instance, engine depot and base maintenance costs, not including fuel and attrition, can exceed engine acquisition costs. This finding is true for current fighter and transport engines.

Depot costs alone can exceed procurement costs.

Component inprovement programs (CIP) conducted during the operational life of an engine can cost as much as it did to develop the engine to its initial model qualification.

If component improvement and whole spare engine procurement are considered ownership costs, then ownership currently constitutes at least two-thirds of total engine life-cycle cost. This is true for current supersonic fighter and subsonic transport/bomber engines.

Satisfying results, in terms of statistical quality, theoretical behavior, and experience from past programs, were obtained from modeling performance/schedule/cost relationships for the development and production of military engines; mixed but promising results were obtained in modeling ownership costs for military engines.

Application of the models obtained in this study indicates that there is a continuing trend in the direction of higher ownership costs, measured in both absolute dollars and as a percentage of total life-cycle costs. Increasing depot cost is the primary reason for this trend. The production cost of the engine (and its parts) is a contributor to depot and base support costs, but so are ownership policies.

The engine maturation process must be more fully understood if improved analytical results are to be obtained and applied to new-engine selection. It takes an engine a long time to mature (commercial experience indicates five to seven years). Consequently, average ownership costs are significantly higher during that period than mature-engine steady-state costs in terms of dollars per flying hour, the yardstick most commonly used. Hopefully, engine monitoring systems should assist in providing designers with the necessary information in the future.

3. Summary of "DESIGN TO LIFE CYCLE COSTS INTERACTION OF ENGINE AND AIRCRAFT" by E J Jones.

The distribution of Life Cycle Costs for a typical combat aircraft between airframe, avionics and engine is discussed. The distribution of Life Cycle Cost for the aircraft between development, production, initial support and operation and support is compared with the distribution for the engine. The effect of fleet size and service life upon the Life Cycle Costs are indicated. The large commitment of Life Cycle Costs early in the conceptual and feasibility phase of the programme is indicated. The choice of engine is an example of this early commitment. The relative effect of the choice of single or twin engine installation, of a de-rated engine or the use of an existing engine upon the engine Life Cycle Costs and the interaction with aircraft costs is discussed. The severe operating conditions for the engine of a combat aircraft are reviewed. Reduced support costs are not expected to give a large-fold return on extra engine development investment.

4. Summary "PROGRESS ON THE US AIR FORCE APPROACH FOR THE PRACTICAL MANAGEMENT OF ENGINE LIFE CYCLE COSTS" Presented by Col Richard E Steere USAF.

This paper presents progress of the USAF efforts to more effectively influence the life cycle costs of newly acquired gas turbine power plants. A combination of technical and business practice initiatives have been undertaken or planned across the entire life cycle spectrum, ie from first entry with the exploratory development program thru' the decision to phase the product out of the active inventory. References are made to earlier papers dealing with the identification and management of life cycle costs, such as, the so called "New Developments Concepts" and the "Engine Structural Integrity Program". This paper addresses the status of those technical and management activities and presents, for the first time, various business concepts and strategies being studied by the US Air Force which complement the earlier initiatives as they impact engine life cycle costs. The role of the USAF Propulsion System Program Office as the continuing focal point for these life cycle efforts will be discussed. The ideas presented are not new as they have been employed successfully at one time or another on an individual basis in the development and support of military and commercial gas turbine power plants. What is new, is the systems management view of the life cycle process and what can be done practically today <u>vs</u> tomorrow to enhance engine life cycle costs in an integrated fashion.

5. Summary "MILITARY AIRCRAFT ENGINE PROGRAMME WITH COST TARGETS" C Foure, SNECMA

This paper discusses some approaches for such programmes; including Value Engineering, reliability and maintainability studies, direct engineering operating cost as considered by the Airlines and technological effort management. Suitable organisation is considered. Cost Prediction techniques should be available at each phase of a programme. Their credibility with regard to 1) the effort needed for their development and 2) the decision to be made on the basis of these results was important. The value conception reviewed and trade off factors discussed. Possible actions are discussed when targets are fixed or revised after initial definition phase; with or without any design changes. Measures for economy needed by fuel cost rises are considered.

6. Summary of "THE APPLICATION OF DESIGN TO COST AT ROLLS-ROYCE" by R J Symon and K J Dangerfield

This paper describes the work done in the Bristol Group of Rolls Royce Aero Division and shows how the Production Cost Control System (of which Design to Cost is part), which from the disappointing experience of value Engineering in the 1960s, is leading to encouraging results and major financial benefits.

A new type of department has been created as timely control of costs require new inter active links between management discipline at all levels.

The extent to which life cycle costs are driven by component costs and the inpact of "Design Liaison" activity during the design cycle is discussed.

Detailed examination of some 2000 detailed drawings of several engines already in production by teams of designers, detail draughtsmen and production engineers gave a very thorough understanding of the origin of unnecessary cost. This emphasised the paramount need for Design, Detail, Development and Production Engineers to work as a team in parallel, for the most cost effective design and manufacturing methods. It lead to the formation of the Production Cost Control Discipline charged as a routine to advise designers on costs as the stress office or weights office does on stress and weights respectively. The objective was to manage cost as the Engine Development and manufacturing Production Programmes were managed. Production Cost Control (PCC) is Design to Cost and Manufacture to Cost.

7. Summary of "*LOGISTICS FORECASTING FOR ACHIEVING LOW LIFE CYCLE COSTS*" by G Walker.

Engines currently under development and some that are now entering military service have been designed under the discipline of Design to minimum Life Cycle Cost (LCC). A major contributor to the achievement of lower LCC has been the adoption of the On Condition Maintenance concept (OCM). OCM provides the potential for reduced LCC by fully utilizing potential parts life and reducing maintenance frequency. Traditional concepts of engine maintenance, which have been based on fixed frequency inspections/overhauls, have required comparatively unsophisticated forecasting to provide adequate logistics support. With the advent of OCM on the other hand, logistics requirements are heavily influenced by wearout characteristics and usage severity. In such cases more sophisticated forecasting methods are required which realistically represent the dynamics of the logistics system inherent in such a maintenance philosophy. If efficient logistics management is to be attained, such forecasting tools should also provide the capability to perform trade-off studies on the cost effectiveness of alternative maintenance or logistics systems. The use of modelling methods which are proving practical in forecasting and trade-off analyses and therefore in establishing an optimum logistics and support environment is explored. Methods discussed include the consideration of wearout characteristics where components exhibit an age-related replacement rate, and also replacement of components which may have a specified maximum life in terms of operating cycles or mission severity. The use of engine history recorders and parts tracking systems and their impact on achieving optimum LCC is also discussed.

8. Summary of "TURBINE ENGINE TECHNOLOGY AND FIGHTER AIRCRAFT LIFE CYCLE COSTS" by F S Timson.

The primary link between aircraft life cycle cost (LCC) and turbine engine technology is the size of the aircraft required to perform a given mission. Many engine characteristics influence fighter aircraft size and LCC. Some of the most important characteristics include thrust-to-weight ratio, specific fuel consumption, bypass ratio, augmentation, and engine life. This paper describes an approach to the analysis of the relationship between fighter aircraft LCC and turbine engine characteristics, using engine thrust-to-weight ratio and mission average specific fuel consumption as examples. The engine selection problem in aircraft configuration/sizing studies is described in terms of the relationship of engine characteristics to aircraft sizing and cost estimating. The use of aircraft LCC carpet plots to analyze LCC sensitivity to engine characteristics is illustrated. The relationship of engine technology and time to these plots is described. Aircraft LCC and gross takeoff weight are compared as measures of merit for selection of engine characteristics. Results are presented for a few typical tactical aircraft. Findings suggested by these analyses are that engine mission average specific fuel consumption is more important than engine thrust-to-weight in determining aircraft LCC, and there may be an economic benefit to accelerating the pace of engine technoloby advancements.

9. Summary of "EVALUATING AND SELECTING THE PREFERRED AIR-BREATHING WEAPON SYSTEM" by Frank A Watts.

Aerospace contractors are continuously attempting to detect new military requirements emanating from changing international threats. In claryifying the requirements and defining a weapon system,contractors are led down multiple paths, depending upon whether they are influenced more by the military technology agencies, the operating commands, the headquarters general staff, of the civilian secretaries.

In arriving at the preferred military system, contractors have established a reputation that is generally accepted by military organisations. Too often, however, these weapon systems fail to pass the budgetary approval process because of inadequate cost analysis. This paper discusses life-cycle costs of three strategic forces, each having equal effectiveness, with the objective of isolating the preferred air-breathing component. Terms are defined, cost elements are reviewed, and an example is described in which various strategic forces containing advanced aircraft are compared and the preferred choice is dependent upon whether least cost is measured by short-term, long-term, or immediate budgetary considerations.

10. CONCLUSION AND OBSERVATION

10.1 It was emphasised repeatedly that operation and support had to be considered and specialist involvement secured at the earliest phase of a project. This view supported the various attempts to quantify the opportunity for reducing operating and support costs at various phases of the project, and the commitment of a very high proportion of the Life Cycle Costs during the concept and definition phase.

10.2 Even so the speakers nearer the "sharp end" of the project the designers, manufacturing specialists and the logistic specialists emphasised that savings of up to 30% could be made during these phases by the use of multi-discipline management techniques; the importance of in service data collection and analysis was emphasised.

10.3 The severe operating conditions for engines particularly in military service was emphasised. On going engine Component Improvement Programmes which were needed throughout the service life of the engine, usually exceeded substantially the cost of development prior to engine qualification. An engine Lead-the-Force programme was a potentially important method to reduce engine operating and support costs.

10.4 It was agreed that advanced engines were a large part of aircraft LCC but the economic benefit of an advanced technology engine was to reduce the aircraft size and so the LCC of the complete system.

10.5 It was important to consider LCC including operating and support costs but near term budget constraints could limit the full implementation of LCC techniques at the project design or selection stage.

THE ROLE OF ADVANCED TECHNOLOGY ON TURBINE ENGINE LIFE CYCLE COST

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United States

SUMMARY

The turbine engine is a major contributing subsystem in the life cycle cost (LCC) of an aircraft weapon system. Advanced technology of turbine engines has a significant impact on LCC, and is addressed in this paper. To adequately assess this advanced technology, LCC techniques are being developed which are sensitive to performance, structural design, manufacturing processes, reliability and maintainability. These techniques are then used to determine the performance/life/cost trade-offs of the advanced technology. An overview of current efforts in LCC techniques, and trade-offs is given.

INTRODUCTION

The overall objectives of our efforts in the area of LCC are two: first, to determine the cost impact of our advanced technology, and second, to identify and pursue those technologies which offer the greatest potential in cost reduction. This paper will include a perspective of turbine engine LCC, and then an overview of current efforts on the methodology and application of design-to-life-cycle-cost.

The LCC of a system can be catagorized into three phases: the Research, Development, Test and Evaluation (RDT&E) phase, the Acquisition phase and the Operation and Support (O&S) phase. Figure 1 shows the LCC of an advanced tactical weapon system. All costs are shown as a percent of total weapon system LCC. A fuel cost of $1.17 per gallon ($0.31 per liter) was used. As can be seen from this figure, the engine, including the fuel it uses, is a major component of weapon system LCC (Ref. 1).

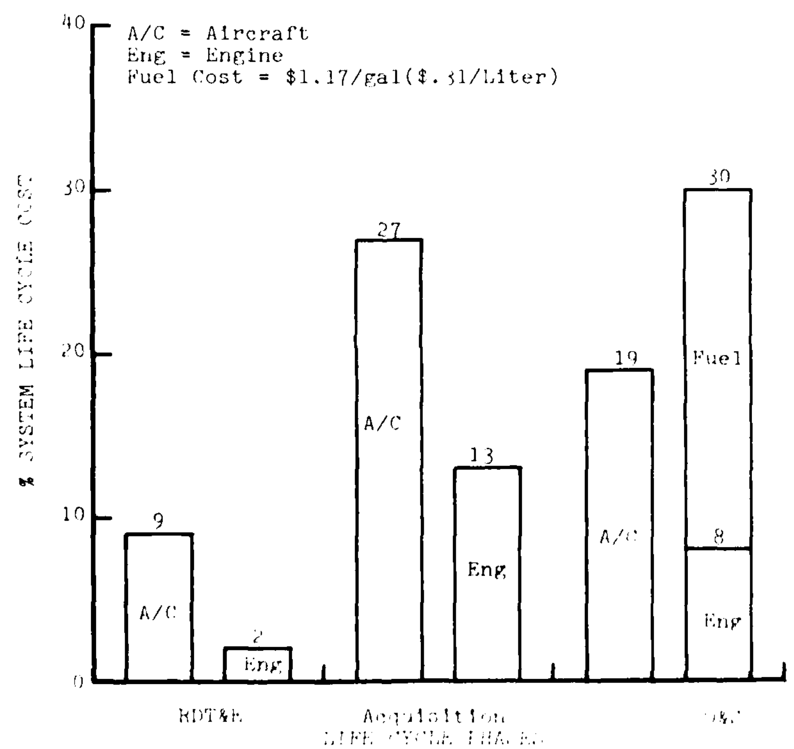

Figure 1 - Life Cycle Cost of an Advanced Tactical Weapon System

LIFE CYCLE PHASES

In the RDT&E phase, the major cost components are design, hardware, and test. Current studies indicate that hardware accounts for 50% of engine RDT&E costs, test for 30% and design for 20%.

In the Acquisition phase, previous cost estimating efforts determined that the single, most significant parameter in estimating the acquisition (or production) cost of an engine is its thrust (Ref. 2). It follows then that the cost per pound of thrust is a relative measure of the acquisition cost of an engine. Figure 2 is a graph of cost per pound of thrust, for military engines in the inventory, plotted against their Military Qualification Test (MQT) date. The cost of engines were normalized to constant year dollars, equivalent production rate, and equivalent production quantity. The slope of the curve shown is a measure of the increase in cost of engines with time.

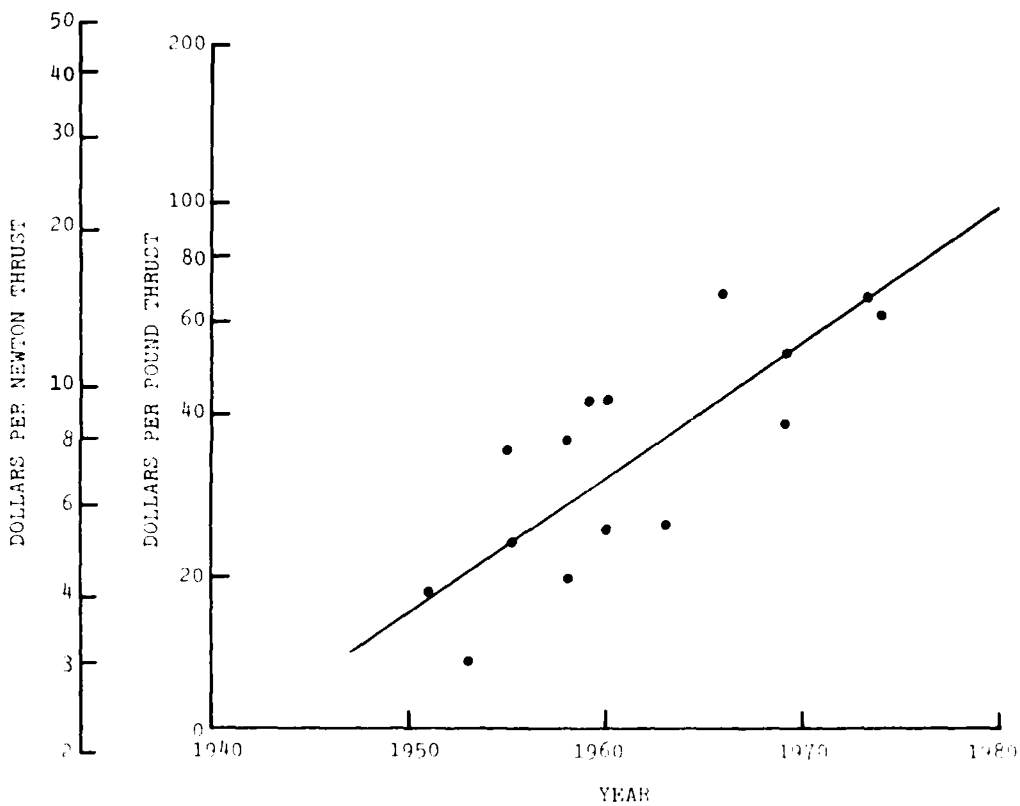

Figure 2 - Turbine Engine Production Cost Trend

Let us now consider the O&S phase. One of the difficulties in this phase is summarized in a Comptroller General of the United States report which states, "It is almost universally held that the greatest obstacle to preparing reliable LCC estimates is the absence of a data base segregating total ownership cost by weapon" (Ref 3). However, we are making gains in this area (Ref. 4). Hardware failures in the O&S phase are a cost driver. Figure 3 shows the basic causes of engine failure. Some of the causes are well understood, others are not. A difficulty encountered in understanding failures, is the combination of two or more basic causes contributing to a failure. The mechanism of failure of these combined causes is difficult to analyze, and the failure difficult to predict.

The operational use of the engine is a major factor in determining its O&S cost. Efforts are going on to understand and quantify this usage effect. Figure 4 is a set of graphs comparing the engine related operational characteristics of two airplanes flying in formation. As can be seen from the graphs in Figure 4, the power setting, engine speed, and tailpipe temperature for the wingman are considerably different than that of the flight leader, even though both airplanes are flying at the same speed and altitude. The resultant temperatures, pressures, and stresses throughout the engines are quite different, and hence, the useful life of certain engine components can be significantly different.

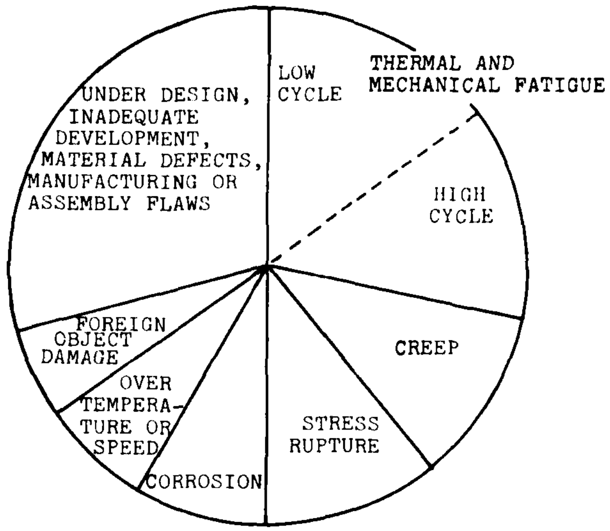

Figure 3 - Causes of Turbine Engine Failures

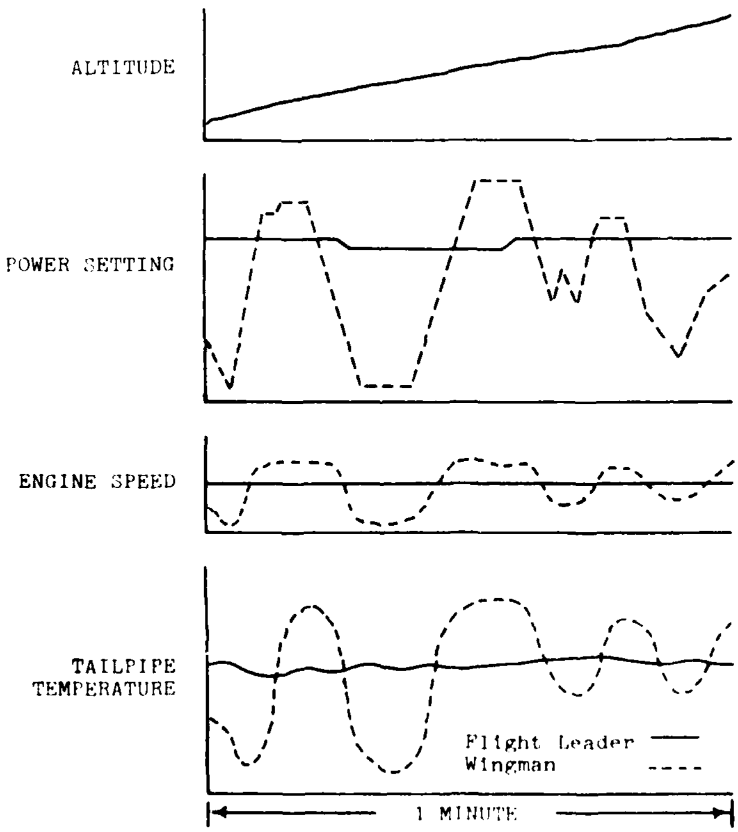

Figure 4 - Turbine Engine Usage

Fuel is becoming a very important factor in the O&S phase. Figure 5 shows the Air Force cost of fuel for the last eight years. Note that the cost of fuel in 1973 was approximately $.11 per gallon ($0.029 per liter). The cost of fuel in 1980 is $1.17 per gallon ($0.31 per liter).

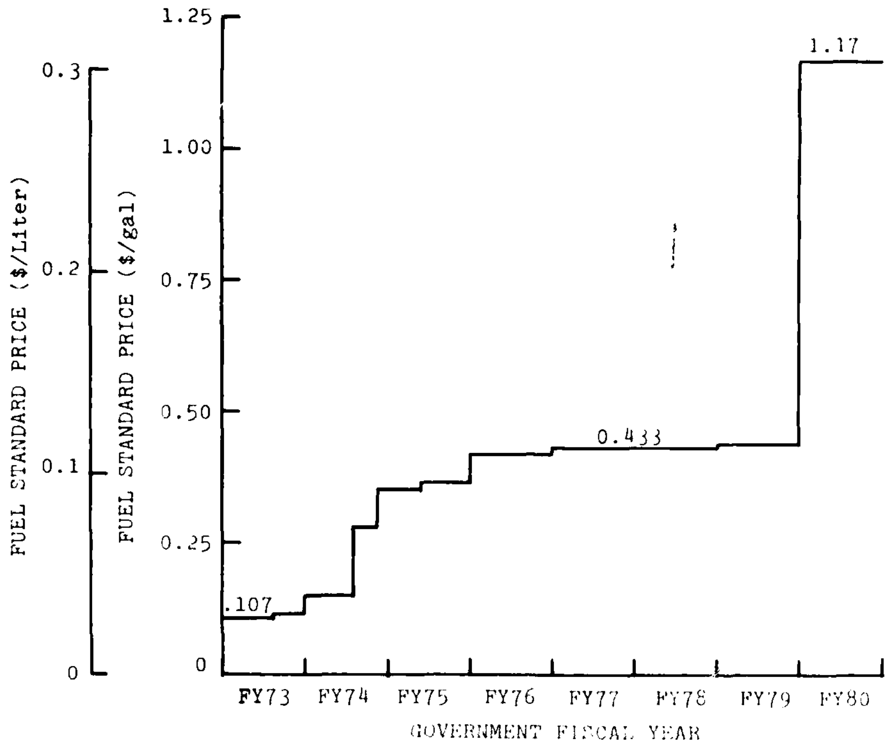

Figure 5 - Turbine Engine Fuel Cost

AIR FORCE/INDUSTRY TURBINE ENGINE LCC MODEL

The key to LCC assessment is a standard, usable methodology. A methodology for use in turbine engine LCC assessment was developed by the Joint Air Force/Industry Working Group in July 1975-April 1976. The methodology defines and organizes all engine chargeable costs. It can discriminate between engine designs, and can be tailored to the specific information known about the engines.

The methodology developed by the Joint Air Force/Industry Working Group includes equations, definitions, and ground rules (Ref. 5). The engine LCC model has twenty-four detailed equations (see Table 1). Most of those equations are used in more than one phase of LCC. The X's on Table 1 denote use of an equation in a particular LCC phase. Twenty-three equations are used to calculate RDT&E costs, fourteen equations to calculate Acquisition costs, and sixteen equations to calculate O&S costs. Each of the equations has several input terms. Each term is completely defined. Definitions are also provided for all output terms to provide clarity in using the model. General instructions and guidelines for model use are as follows: (1) The model was developed to be used primarily in source selections as opposed to other applications such as implementing warranties. (2) The model's primary value is not for absolute engine LCC, but comparative LCC of alternate engine designs. (3) The model was designed to break down the engine to the part level. However, the capability of going to the part level should be used only as required. (4) Of the twenty-four equations in the engine LCC model, only the appropriate equations for a given application should be used. (5) Costs are shown in government fiscal years and will include General and Administrative (G&A) Cost, but will exclude profit and fee.

REDUCED COST TURBINE ENGINE CONCEPTS PROGRAM

There are major efforts underway to adapt the methodology described in the previous section for LCC analysis during advanced technology programs. In June 1977, the Reduced Cost Turbine Engine Concepts program was initiated. The objectives of this effort are to: (1) assess reduced cost turbine engine concepts prior to engineering development in terms of their impact on engine RDT&E cost, engine Acquisition cost, engine O&S cost, and system LCC; (2) select an engine component concept which offers significant cost reduction based on this assessment; (3) design, fabricate, and test

TABLE 1

AIR FORCE/INDUSTRY TURBINE ENGINE LCC MODEL

	COST ELEMENT	R	A	S
1.	Conceptual Study, Cycle and Configuration	X		
2.	Mock-Up	X		
3.	Detail Design	X		X
4.	Tooling	X	X	
5.	Engine Manufacturing	X	X	X
6.	Spare Sections Assemblies and Parts	X	X	
7.	Peculiar Support Equipment	X	X	X
8.	Common Support Equipment	X	X	
9.	Special Test Equipment	X	X	X
10.	Packaging and Shipping	X	X	X
11.	Facilities	X	X	
12.	Contractor Test	X		X
13.	Government Testing	X		X
14.	Training	X	X	X
15.	Contractor Field Support	X	X	X
16.	Data	X	X	X
17.	Initial Inventory Management	X	X	
18.	Recurring Inventory Management	X		X
19.	Scheduled Maintenance	X		X
20.	Unscheduled Maintenance	X		X
21.	Recurring Maintenance Management	X		X
22.	System Engineering/ Project Management	X	X	X
23.	Petroleum, Oil and Lubrication	X		X
24.	Production Program Start-Up		X	

R - Research Development Test & Evaluation
A - Acquisition
S - Operation and Support

the selected component concept; and (4) reassess the component concept LCC impact based upon the design, fabrication and test results. This effort will demonstrate the use of LCC as a major design parameter.

Reduced Cost Turbine Engine Concepts Approach

The Reduced Cost Turbine Engine Concepts Program includes the development of a LCC model based on the Air Force/Industry Turbine Engine LCC model to determine engine RDT&E cost, engine acquisition cost, engine O&S cost and system LCC as a function of turbine engine component design parameters. These component design parameters include performance, weight, life and maintainability. The LCC model is then used to determine the LCC of some advanced technology aircraft system for use as a baseline. Trade studies are then conducted relative to this baseline. The results of the trade studies are used to select a component concept for design, fabrication and test. As data is obtained during the design, fabrication, and test phases, the LCC model is updated and the impact on LCC determined.

Reduced Cost Turbine Engine Concepts LCC Model

The cost elements used in the LCC model to define turbine engine LCC were obtained from the Air Force/Industry Turbine Engine LCC model addressed previously. Not all cost elements given on Table 1 are used in the developed model. The equations marked with an "X" on Table 2 are used in the appropriate LCC phase. For example, cost element 3 will be used during RDT&E and O&S. Equations were selected for use on the basis of their percent contribution to engine LCC in the most likely cases. For example, results indicate that Petroleum, Oil and Lubrication accounts for approximately [illegible] of engine LCC, Manufacturing accounts for approximately [illegible] of engine LCC, and Scheduled and Unscheduled Maintenance accounts for [illegible] of engine LCC. The other cost elements given on Table [illegible] account for the remaining [illegible] of engine LCC.

The LCC model developed by this effort uses both accounting and parametric cost estimating relationships. Figure [illegible] gives examples of parametric cost estimating relationships and accounting cost estimating relationships. A parametric cost estimating relationship is an empirical equation for some element of LCC in terms of design parameters. An accounting cost estimating relationship is a summation of [illegible], material costs and overhead costs.

Figure 7 is a simplified schematic of the LCC model developed by this program. The model calculates engine RDT&E cost, engine Acquisition cost, engine O&S cost and system LCC as a function of engine component life, weight, performance and maintainability. Engine RDT&E costs are calculated using parametric cost estimating relationships. Engine Acquisition costs are calculated using accounting cost estimating relationships. Costs are accumulated at the component level. Learning curves are used to account for changes in cost as a function of production quantity. Scaling laws are provided to account for changes in baseline engine size. Engine O&S costs are calculated using either a simulation or a discrete model. A complete explanation of a simulation versus a discrete model is beyond the scope of this paper. It will simply be stated that the simulation model provides a more realistic representation of the O&S

TABLE 2

REDUCED COST TURBINE ENGINE CONCEPTS LCC MODEL

	COST ELEMENT	R	A	S
1.	Conceptual Study, Cycle and Configuration			
2.	Mock-Up			
3.	Detail Design	X		X
4.	Tooling	X	X	
5.	Engine Manufacturing	X	X	X
6.	Spare Sections Assemblies and Parts	X	X	
7.	Peculiar Support Equipment			
8.	Common Support Equipment			
9.	Special Test Equipment	X		
10.	Packaging and Shipping			X
11.	Facilities			
12.	Contractor Test	X		
13.	Government Testing			
14.	Training			
15.	Contractor Field Support			X
16.	Data			
17.	Initial Inventory Management			
18.	Recurring Inventory Management			
19.	Scheduled Maintenance	X		X
20.	Unscheduled Maintenance			X
21.	Recurring Maintenance Management			
22.	System Engineering Project Management	X		
23.	Petroleum, Oil and Lubrication	X		X
24.	Production Program Start-Up			

R - Research Development Test & Evaluation
A - Acquisition
S - Operation and Support

PARAMETRIC COST ESTIMATING RELATIONSHIP

COST = f (THRUST, WEIGHT, ETC.)

ACCOUNTING COST ESTIMATING RELATIONSHIP

$$\text{COST} = \sum_{i=1}^{n} (\text{LABOR RATE}_i) \times (\text{MAN-HOURS}_i) + (\text{MATERIAL WEIGHT}_i) \times (\text{MATERIAL PRICE PER POUND}_i)$$

n = TOTAL NUMBER OF PARTS

Figure 6 - Parametric Versus Accounting Cost Estimating Relationship

phase of the engine life cycle. The discrete model has the advantage of using less computer processing time and storage. Both models account for scheduled maintenance as a function of engine operating hours, flights or periods, and employ learning curves for required maintenance actions. Both models account for unscheduled maintenance by employing failure distributions for individual engine components and learning curves for resultant maintenance actions. Fuel is determined as a function of usage and engine fuel flow. All phases of airframe LCC are determined using parametric cost estimating relationships. These cost estimating relationships define airframe RDT&E, Acquisition, and O&S costs in terms of engine and airframe interface parameters.

Reduced Cost Turbine Engine Concepts Methodology

All LCC trade studies are conducted relative to the baseline system LCC. During these studies, the following parameters initially are constant: mission, life-time, fleet buildup and peacetime usage rates. The baseline engine and airframe will be scaled in size to meet fixed mission requirements, and the cost impact then determined. The trade studies will be conducted applying inflation and discounting, or constant year dollars.

ENGINE

RDT&E
- o Cost Estimating Relationships (CER)

ACQUISITION
- o Part Level
- o Learning Curves
- o Scaling

O&S
- o Fuel
- o Scheduled Maintenance
  - - Operating Hours
  - - Flight
  - - Period
  - - Learning Curves
- o Unscheduled Maintenance
  - - Failure Distributions
  - - Learning Curves

AIRFRAME

RDT&E
- o CER

ACQUISITION
- o CER

O&S
- o CER

ECONOMICS
- o Inflation
- o Discounting
- o Constant Year Dollars

Figure 7 - Reduced Cost Turbine Engine Concepts
Life Cycle Cost Model

Figure 8 shows that a change in baseline engine component performance requires the use of an engine performance model, an aircraft sizing/mission analysis model and the LCC model. A change in baseline engine component weight requires a reassessment of baseline engine weight, resizing of the baseline aircraft, and the use of the LCC model to determine the LCC impact. Changes in baseline engine component life, maintainability, and acquisition cost require only the use of the LCC model.

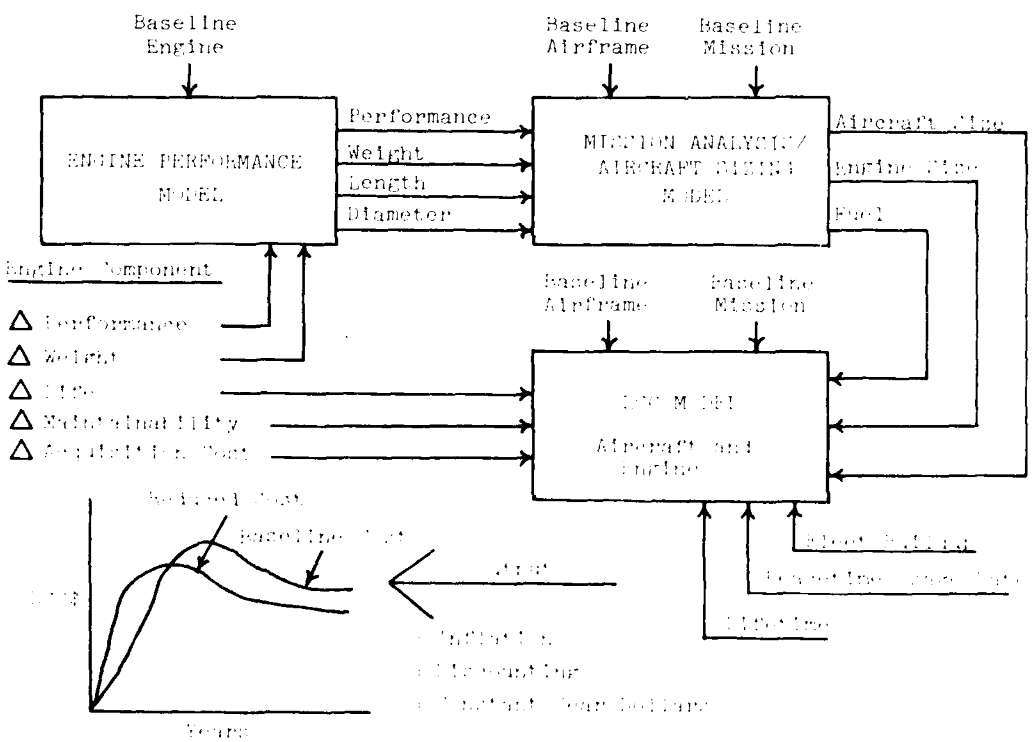

Figure 8 - Reduced Cost Turbine Engine Concepts
Life Cycle Cost Methodology

Reduced Cost Turbine Engine Concepts - Results

To date, several trade studies have been completed during the Reduced Cost Turbine Engine Concepts Program. This section of the report will address some of those trade studies.

One example is the use of powder metal to manufacture, to near net shape, several components in the high spool of an advanced technology engine. This process results in decreased forging operations and improved material utilization. A reduction in engine manufacturing cost is realized as shown on Table 3. Note that baseline engine performance, weight, reliability, life and maintainability are not affected and no scaling of the baseline engine or aircraft is required to determine the LCC payoff.

TABLE 3

POWDER METAL HIGH PRESSURE SPOOL LIFE CYCLE COST IMPACT IN 1978 DOLLARS

INPUT	
OPERATIONAL LIFE = 20 YR	OPERATIONAL AIRCRAFT = 334
ENGINES/AIRCRAFT = 2	UTILIZATION = 300 HRS/YR/AIRCRAFT
	BASELINE SIZE
ENGINE PERFORMANCE	NO IMPACT
ENGINE WEIGHT	NO IMPACT
ENGINE RELIABILITY/LIFE	NO IMPACT
ENGINE MAINTAINABILITY	NO IMPACT
ENGINE MANUFACTURING COST	-$17,461.00(250th unit)
OUTPUT	
ENGINE RDT&E COST	-$ 1,654,295.00
ENGINE ACQUISITION COST	-$35,759,279.00
ENGINE O&S COST	-$41,870,450.00
TOTAL WEAPON SYSTEM LCC	-$79,284,024.00

A second study, using the same baseline engine and aircraft as in the first study, was conducted to determine the LCC impact of powder metal versus a eutectic composition high pressure turbine blade. The study was conducted assuming no engine performance, weight or maintainability impact. It was only necessary to determine the life, and manufacturing cost impact of the various blades. The eutectic blade was found to have an increase of 4 times the life of the baseline blade, and an increase of 1.[illegible] times the cost. The powder metal blade had an increase of 2.5 times the life of the baseline blade material and an increase of 1.3 times the cost. The results of the studies are shown on Tables 4 and 5.

TABLE 4

EUTECTIC HIGH PRESSURE TURBINE BLADE LIFE CYCLE COST IMPACT IN 1978 DOLLARS

INPUT	
OPERATIONAL LIFE = 20 YR	OPERATIONAL AIRCRAFT = [illegible]34
ENGINES/AIRCRAFT = [illegible]	UTILIZATION = 300 HRS/YR/AIRCRAFT
	BASELINE SIZE
ENGINE PERFORMANCE	NO IMPACT
ENGINE WEIGHT	NO IMPACT
ENGINE RELIABILITY/LIFE	4X
ENGINE MAINTAINABILITY	NO IMPACT
ENGINE MANUFACTURING COST	1.[illegible]X
OUTPUT	
ENGINE RDT&E COST	+$ [illegible]
ENGINE ACQUISITION COST	+$ [illegible]
ENGINE O&S COST	-$[illegible]
TOTAL WEAPON SYSTEM LCC	-$[illegible]

TABLE 5

POWDER METAL HIGH PRESSURE TURBINE BLADE LIFE CYCLE COST IMPACT IN 1978 DOLLARS

INPUT	
OPERATIONAL LIFE = 20 YR	OPERATIONAL AIRCRAFT = 334
ENGINES/AIRCRAFT = 2	UTILIZATION = 300 HRS/YR/AIRCRAFT
	BASELINE SIZE
ENGINE PERFORMANCE	NO IMPACT
ENGINE WEIGHT	NO IMPACT
ENGINE RELIABILITY/LIFE	2.5X
ENGINE MAINTAINABILITY	NO IMPACT
ENGINE MANUFACTURING COST	1.3X
OUTPUT	
ENGINE RDT&E COST	+ $1,527,041.00
ENGINE ACQUISITION COST	+ $25,524,920.00
ENGINE O&S COST	-$148,329,765.00
TOTAL WEAPON SYSTEM LCC	-$121,277,804.00

A third study considers a transpiration cooling material which is a laminated, photoetched, diffusion bonded structure. This material has three laminated sheets. Because of the alignment of adjacent sheets, the air must travel around the etched pins in each sheet. This material has a higher heat transfer effectiveness than conventional film cooling, and when compared to other transpiration materials it has improved structural integrity, oxidation resistance, and tolerance to clogging.

This transpiration cooled material is used in the construction of combustion liners. Table 6 shows that this material will result in a decrease in baseline engine cooling flow, a reduction in baseline engine weight, an increase in baseline engine life, and a lower baseline engine manufacturing cost. The LCC problem becomes somewhat more involved than the previous examples. The reduction in engine cooling flow and weight necessitates engine and system scaling to identify the full LCC payoff of the combustor. Table 6 gives the results for the engine and airframe which are scaled from the baseline.

TABLE 6

TRANSPIRATION COOLED COMBUSTOR LIFE CYCLE COST IMPACT IN 1978 DOLLARS

INPUT		
OPERATIONAL LIFE = 10 YR	OPERATIONAL AIRCRAFT = 750	
ENGINES/AIRCRAFT = 2	UTILIZATION = 300 HRS/YR/AIRCRAFT	
	BASELINE SIZE	SCALED SIZE
ENGINE PERFORMANCE	-27% COOLING FLOW	-3% AIRFLOW
ENGINE WEIGHT	-17.87 LB.(-8.106Kg)	-87.8 LB.(-39.8[illegible]Kg)
ENGINE RELIABILITY/LIFE	3X LIFE	3X LIFE
ENGINE MAINTAINABILITY	NEGLIGIBLE	NEGLIGIBLE
ENGINE MANUFACTURING COST	- $4,385.00 (AVG. OF FIRST 2000 UNITS)	- $36,856.00 (AVG. OF FIRST 2000 UNITS)
OUTPUT		
ENGINE RDT&E COST		- $4,410,000.00
ENGINE ACQUISITION COST		- $60,100,000.00
ENGINE O&S COST		- $34,380,000.00
TOTAL WEAPON SYSTEM LCC		-$353,[illegible]13,[illegible]00.00

A fourth study determines the cost impact of a low aspect ratio fan of advanced aerodynamics. Table 7 indicates that this low aspect ratio fan results in an increase in baseline engine performance, an increase in baseline engine weight, an increase in baseline engine mean time between failure (MTBF), and a lower baseline engine manufacturing cost. Note that with the exception of the increase in baseline engine weight, all baseline engine changes should result in a decrease in LCC. Table 7 gives the LCC impact for the engine which is scaled.

TABLE 7

LOW-ASPECT-RATIO FAN LIFE CYCLE COST IMPACT IN 1978 DOLLARS

INPUT		
OPERATIONAL LIFE = 20 YR	OPERATIONAL AIRCRAFT = 700	
ENGINES/AIRCRAFT = 2	UTILIZATION = 1116 HRS/YR/AIRCRAFT	
	BASELINE SIZE	SCALED SIZE
ENGINE PERFORMANCE	+4% THRUST -3% SPECIFIC FUEL CONSUMPTION (SFC)	-4% AIRFLOW
ENGINE WEIGHT	+10 LB.(+4.536Kg)	-14.5 LB.(-6.577Kg)
ENGINE RELIABILITY/LIFE	+30% MTBF	+30% MTBF
ENGINE MAINTAINABILITY	NO IMPACT	NO IMPACT
ENGINE MANUFACTURING COST	-$9,298.00 (AVG. OF FIRST 1400 UNITS)	-$11,385.00 (AVG. OF FIRST 1400 UNITS)
OUTPUT		
ENGINE RDT&E COST		NO IMPACT
ENGINE ACQUISITION COST		-$17,078,000.00
ENGINE O&S COST		-$38,936,000.00
TOTAL WEAPON SYSTEM LCC		-$89,378,000.00

A fifth study considers the use of a low aspect ratio turbine in an advanced technology turbine engine. Table 8 indicates that the low aspect ratio turbine will result in an increase in baseline engine performance, an increase in baseline engine weight, a decrease in baseline engine reliability, a decrease in baseline engine maintainability (Time Between Overhaul, TBO) and an increase in baseline engine cost. Note that all of the baseline engine changes with the exception of SFC and thrust result in an increase in baseline engine and aircraft LCC. Scaling of the engine and airframe is required to realize the LCC payoff of the low aspect ratio turbine. Table 8 gives the results.

TABLE 8

LOW-ASPECT-RATIO BLADING FOR HIGH PRESSURE TURBINE
LIFE CYCLE COST IMPACT IN 1978 DOLLARS

INPUT		
OPERATIONAL LIFE = 15 YR	OPERATIONAL AIRCRAFT = 420	
ENGINES/AIRCRAFT = 2	UTILIZATION = 300 HRS/YR/AIRCRAFT	
	BASELINE SIZE	SCALED SIZE
ENGINE PERFORMANCE	+6.41% Thrust -1.33% SFC	-10.6% AIRFLOW
ENGINE WEIGHT	+7.8 LB.(+3.538Kg)	-99 LB.(-44.906Kg)
ENGINE RELIABILITY/LIFE	-10% MTBF	-10% MTBF
ENGINE MAINTAINABILITY	-10% TBO	-10% TBO
ENGINE MANUFACTURING COST	+$2000.00 (AVG. OF FIRST 50 UNITS)	-42,000.00 (AVG. OF FIRST 50 UNITS)
OUTPUT		
ENGINE RDT&E COST		- $6,680,806.00
ENGINE ACQUISITION COST		- $36,161,188.00
ENGINE O&S COST		- $76,873,66[illegible].00
TOTAL WEAPON SYSTEM LCC		-$172,100,000.00

COST REDUCTION POTENTIAL - EXISTING ENGINE

The life cycle cost of existing engines can also be reduced with the application of advanced technology to these engines. A study is being conducted to identify and demonstrate the potential of upgrading the T56 engine in the C130 aircraft. The T56 engine would be upgraded to an improved configuration. The improved engine has a 3%

increase in compressor efficiency, a 1.7% increase in turbine efficiency and a 7% increase in turbine inlet temperature. The mission fuel savings range from 6.7% to 10.7% for this improved T56 engine.

The LCC model previously discussed was used to identify the LCC savings. The ground rules for this study are shown in Table 9.

TABLE 9

T56 ENGINE LIFE CYCLE COST STUDY GROUNDRULES

BASE YEAR FOR STUDY	1978
NUMBER OF AIRCRAFT RE-ENGINED	582
NUMBER OF ENGINES CONVERTED TO THE IMPROVED CONFIGURATION	2677
23-YEAR LIFE CYCLE	
RDT&E	1982-1985
FLEET BUILDUP	1985-1990
STEADY-STATE OPERATION	1990-2005
AIRCRAFT UTILIZATION RATE	52 HRS/MONTH

The payback time periods for the improved T56 engine are shown in Figure 9, as a function of fuel cost. This study has shown the large effect of cost of fuel on the potential cost savings.

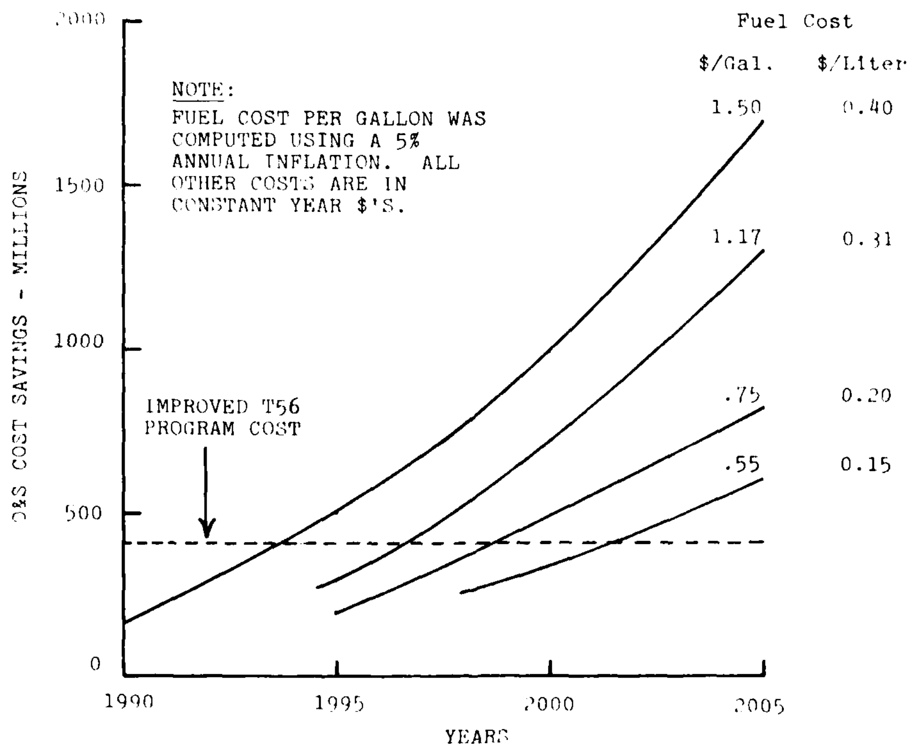

Figure 9 - Improved T56 Engine Cost Savings

ADVANCED TECHNOLOGY COST REDUCTION POTENTIAL

Future technologies can reduce the LCC of advanced engines. Several technologies that offer LCC reduction potential, in addition to those previously discussed, were investigated. The following advanced technologies shown in Table 10 offer the greatest payoff in the LCC reduction of advanced engines. The cost savings were adjusted to apply to a 2-engine tactical aircraft. The savings are shown in terms of engine cost reduction percentage. With careful attention to LCC, the next generation engines could achieve this level of LCC reduction by incorporating similar advanced technologies.

TABLE 10

ADVANCED TECHNOLOGY COST REDUCTION POTENTIAL

	RDT&E	ACQ	O&S	LCC
POWDER METAL HIGH PRESSURE SPOOL	-1.2%	3.09%	-0.62%	-1.84%
EUTECTIC COMPOSITION HIGH PRESSURE TURBINE (HPT) BLADES	-	+1.09%	-9.31%	-4.35%
TRANSPIRATION COOLED COMBUSTOR	-1.22%	-2.4%	-2.0%	-2.1%
TRANSPIRATION COOLED HPT STATOR	-	-0.8%	-1.5%	-1.0%
LOW ASPECT RATIO COMPRESSOR	-	-5.5%	-2.3%	-2.7%
LOW ASPECT RATIO FAN - 2-STAGE	-	-5.5%	-2.3%	-2.7%
ADVANCED LOW PRESSURE TURBINE	-	-3.0%	-4.0%	-4.0%

CONCLUSIONS

Figure 10 was shown previously, with one addition. The estimated cost of an advanced tactical engine is shown by the crosshatched area to the right of the figure. With a conscious effort to apply advanced technology in the most cost effective manner, the estimated cost of an advanced engine, as shown in Figure 10, is a realistic goal.

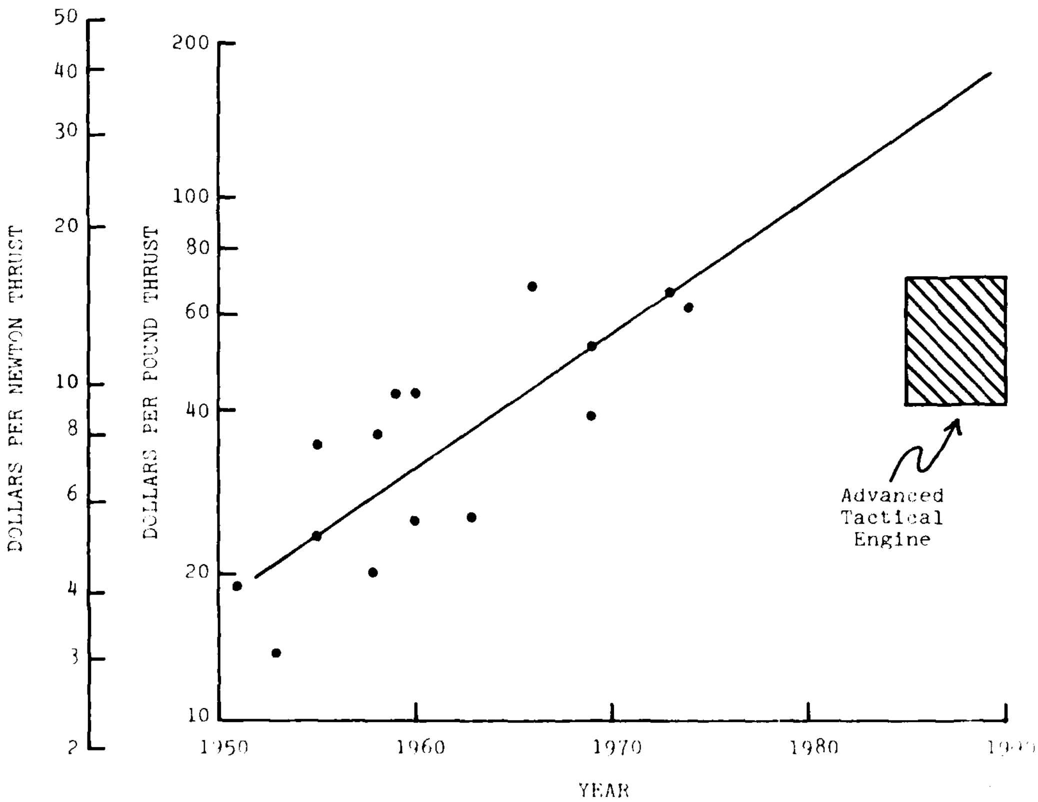

Figure 10 - Inventory Versus Advanced Turbine Engine Production Cost Trend

The turbine engine is a major contributor to weapon system LCC. The consideration of its contribution early in the design phase will result in a substantial LCC savings. When determining the LCC impact of an advanced technology engine component, the following should be considered: (1) weapon system LCC, not just engine LCC, (2) engine component interaction, (3) duty cycle, (4) fuel cost and usage, and (5) engine component maintenance and life prediction. The accurate determination of all of these parameters is essential to the prediction of the LCC payoff of advanced technology turbine engine components. The need and the challenge are clear.

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COST CONSIDERATIONS OF ENGINE FUEL CONTROL SYSTEMS

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ENGLAND

SUMMARY

Hydromechanical fuel control systems are complex mechanisms the manufacture of which is highly labour intensive. It is our experience that by applying well tried principles a value engineering team can identify considerable potential savings, particularly in the case of new designs. While lower life cycle costs are frequently only achieved at the expense of increased first cost this is not invariably so.

The value engineering exercise itself should be as cost effective as possible, therefore, a small, closely monitored, project dedicated team is favoured.

It is important that he designer should have taken account of the basic principles of value engineering when arriving at his original design.

INTRODUCTION

The scope of the paper is based upon the Company's activity in design and manufacture of fuel control systems for aircraft gas turbine engines. It is concerned largely with the hydromechanical part of the system as this is the area which has offered the greatest reward from attention to value engineering methods.

REQUIREMENTS AND CONFIGURATION OF A FUEL CONTROL SYSTEM

The fuel control system for a gas turbine engine consists of a number of elements which can be either all hydromechanical or part hydromechanical and part electronic.
The various configurations are shown in the block diagram, Fig 1.

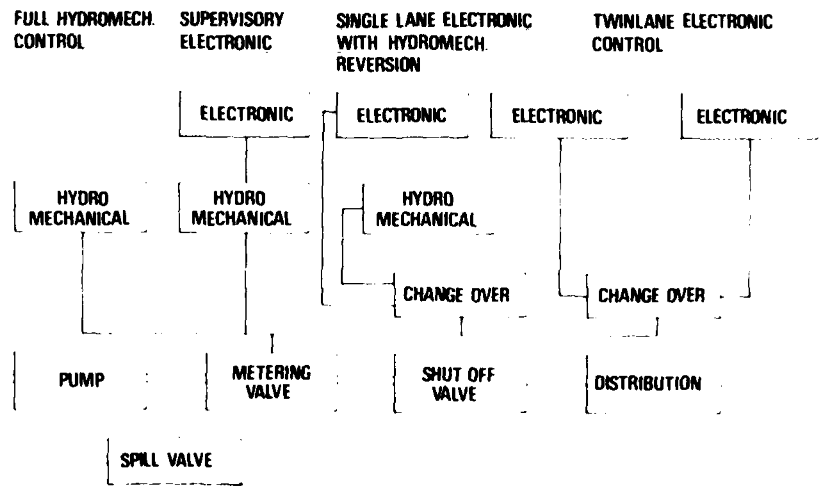

FIG 1 - ALTERNATIVE CONTROL CONFIGURATIONS

The basic elements which, because of their need to handle the fuel directly, must always be hydromechanical consist of :

1 A Pump to provide the required volume of fuel at a pressure sufficient to ensure satisfactory combustion and control.

2 A Spill Valve if the pump is not of the variable output type.

3 A Metering Valve to vary the flow of fuel in accordance with the requirements of the engine under varying operating conditions and in response to the pilot's demands.

4 A Shut-Off Valve to enable the fuel supply to be cut off in order to shut down the engine.

5 A Distribution System to balance the fuel fed into the several points of entry of the Combustion System.

Each of these may be more or less complicated according to the particular application. Thus the total pumping package may include a backing pump, main pump, relief valve, an integral filter, possibly a speed probe and also an alternator to power the control electronics.

In addition to the basic elements through which the fuel flows from the tanks to the combustion system, appropriate means must be provided for computing the actual require--ments of the engine under any operating conditions whilst still taking account of the demands made by the pilot. Typically such computing controls will act upon or in association with the metering valve. They may be either completely hydromechanical, hydromechanical with a supervisory electronic trim, a single lane electronic control with the facility to revert to a simple hydromechanical control in the event of failure or they may be in the form of a twin lane electronic control.

Where electronic controls are incorporated they will operate the hydromechanical part of the system through a variety of electromechanical interfaces and they may be analogue or, as in more recent systems, digital in principle.

By providing reliable and accurate control of the engine without attention over long periods of operation the fuel system can make a major contribution to optimising the life cycle costs of the aircraft.

RELATIVE COST OF THE FUEL CONTROL SYSTEM

In terms of first cost the fuel control system may be put into perspective by comparing its cost with that of the engine.

In general the cost of the fuel system is a smaller proportion of total engine cost for larger engines, but increases with increasing engine complexity. Thus the cost of the control will vary from about 5 to 10 per cent of the total cost of the engine according to size and application. As this represents probably less than 3% of the total cost of the aircraft it will be evident that improvements in the reliability and durability of the control will probably offer greater potential for reducing the life cycle costs of the total aircraft than a reduction in its first cost will have on the acquisition cost of the aircraft.

Typical values for relative cost according to application are given in TABLE 1.

APPLICATION	PROPORTION OF TOTAL ENGINE COST - PER CENT (TYPICAL)	
LARGE TRANSPORT	5	1
MEDIUM TRANSPORT	6	2
COMPLEX MILITARY	11	3
SIMPLE MILITARY	7	4
TURBOSHAFT	9	5
GENERAL AVIATION	8	6

Notes :
1 $>$ 20,000 lbs thrust
2 10 - 20,000 lbs thrust
3 With reheat
4 Without reheat
5 Helicopters
6 Turboprops and turbojets $<$ 10,000 lbs thrust

TABLE 1 : RELATIVE COST OF FUEL CONTROL SYSTEMS

FACTORS CONTRIBUTING TO THE COST OF FUEL CONTROLS

All components which contribute to the efficient, safe and reliable operation of an aircraft tend to be inherently expensive. It is of interest to consider here those particular factors which are important in contributing to the cost of hydromechanical fuel controls. These are :

1 Complexity :

The mechanisms contain a large number of small intricately shaped and densely packed parts.

2 Small Quantities :

Because orders for any given system rarely exceed more than 50 per month, parts are usually made by small batch production techniques which frequently prevents the economical development of more cost effective methods. However, NC machining methods can be particularly worthwhile for this type of production and are widely practised.

3 Little Commonality :

In general the control system for each application is different whether for civil, industrial, helicopter or military with little commonality of hardware.

4 Few repetitive parts :

Unlike, say, the core of an engine which contains many complex but identical blades, all parts tend to be different so rarely justify the use of large scale manufacturing methods.

5 Close Tolerances, Fits and Surface Finishes :

These are necessary both to meet close unit specification limits and because of the need to operate efficiently immersed in fuel.

6 Hostile Operating Medium :

The fuel in which the various operating mechanisms are required to function has, at best, very poor lubricating properties. It is also frequently hot and sometimes contaminated. This demands the development and use of advanced materials and processes, particularly for bearings, seals and other elastomeric items.

7 Restricted Space :

Because of the need to contain the fuel system in the small space between the cylindrical engine and the also generally cylindrical outer casing, the volume offered by the engine maker to the fuel system designer is frequently both small and of less than optimum shape.

At the outset the following generally applicable principles which would lead to the most cost effective system can be accepted :

- for low first cost :

  Simple system

  Few components

  Widest use of standard parts

  Cost effective manufacturing techniques

  PLUS

- for low life cycle cost

  High reliability

  Good maintainability

  Long life

  Low cost spares

  Adequate performance

FACTORS AFFECTING PRICE

Before proceeding further with detailed discussion of fuel systems it is worthwhile examining the factors which can affect the price of such a product and the relative contribution which can be made to each factor by the supplier and customer acting together as a team.

Five principal factors are shown diagrammatically in Fig 2, with an indication of the level of responsibility which can be attributed to the customer and supplier in each case. Although they are considered separately here it must be appreciated that they will all interact to affect the price :

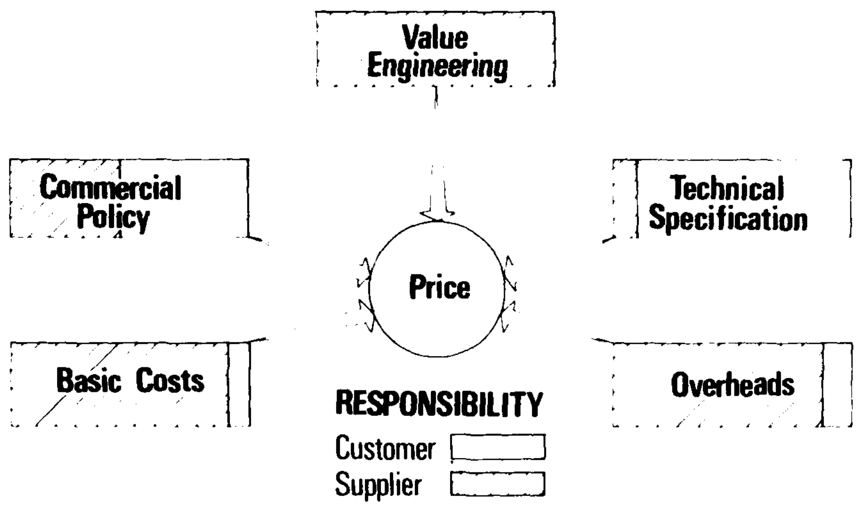

FIG 2 - BASIC FACTORS AFFECTING PRICE

Technical Specification :

While this is clearly principally the responsibility of the customer, the supplier should be expected and, indeed, encouraged to play his part by drawing attention to those areas of the specification which because they are unduly demanding or restrictive, are likely to contribute adversely to his costs.

Basic Costs :

Derived from direct labour hours, wage rates, material prices, etc, these are largely controlled by the supplier but they can be adversely affected by the customer if he requires operations to be performed which are not entirely necessary to satisfy the technical specification. Typical examples, would be operations which merely improve the appearance of a part, the adoption of costly fastener standards and uneconomical weight saving practices.

Overheads :

Although the supplier is the primary controller of this factor the customer can add to the supplier's overheads by demanding unnecessarily restrictive quality control procedures or other operating systems.

Commercial Policy :

Both parties have an equal responsibility here for such aspects as buying policy, pricing, cost estimating, contract conditions, warranties, etc.

Value Engineering :

This is entirely the responsibility of the supplier but through its interaction with the other factors, particularly the technical specification, the customer will become involved indirectly.

BASIC COMPONENTS OF COST AND THEIR EFFECT

The cost structure of a typical hydromechanical fuel control is shown diagrammatically in Fig 3. It will be seen that as much as 90% of the cost of the system is accounted for by labour which is charged at the full production rate including overheads, with labour for machining and associated operations taking by far the largest share.

This distribution is quite unlike that for the engine which can have a purchased content as high as 60%. It also differs markedly from that of electronic parts of the system for which the purchased items are of the order of 50% of the total cost. Thus any meaningful economies in a chosen hydromechanical control must come largely through our own efforts within our own organisation.

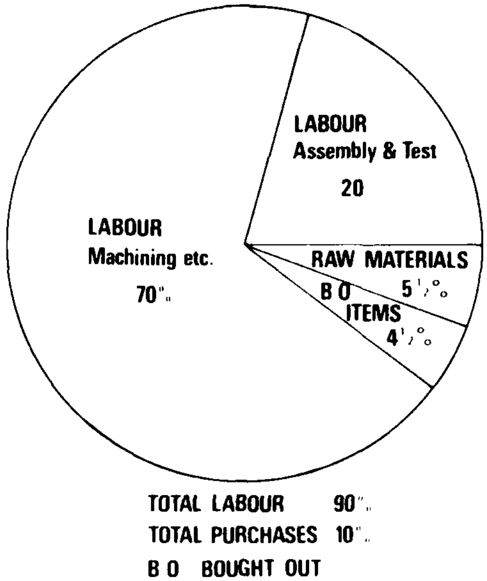

FIG 3 - COST STRUCTURE OF A TYPICAL HYDROMECHANICAL FUEL SYSTEM

The most effective way of optimising the first cost of the selected system therefore, is to minimise the amount of labour required for the con version of materials. Test schedules must also be examined closely in relation to the technical specification to ensure that no unnecessary tests or procedures are adding to the labour content.

Since only a very small part of the total cost (5½% in the example shown) is spent on raw materials little is to be gained from a reduction in material costs alone. However, there are two important ways in which an effective contribution to minimising costs can be derived from materials :

1 By selecting those materials which have the best manufacturing characteristics, typically ease of machining. For instance, the replacement of a very difficult to machine soft magnetic iron in a solenoid by a free machining stainless iron with acceptable magnetic properties and which also has the added virtue of not requiring to be protected from corrosion by electroplating.

2 By presenting the material in a form which requires fewer machining operations or simply less metal removal. Examples are the use of a close to form forging or casting instead of wrought bar or a precision investment casting instead of a sand or gravity die casting. Powder metallurgy can appear attractive for some parts but its application is generally limited by the small numbers which are needed for the expected total run of the product.

In adopting the first of these methods, any small premium which might have to be paid for improved raw material will almost certainly be heavily outweighed by reduced manufacturing costs.

Method 2 will almost invariably result in an actual increase in material cost which, to be worthwhile, must be more than balanced by the savings obtained from reduced machining. Since allowance must also be made for amortisation of the additional cost of any patterns or special tooling which might be needed, the use of special forms of material becomes more attractive the greater the total production quantity is to be. This clearly demands knowledge of accurate sales forecasts.

The effectiveness of a change of material form compared to simply reducing the cost of material is illustrated in Table 2. In this notional example a 50% reduction in material cost alone is shown to be less advantageous than a 50% increase in material cost which permits a 10% decrease in machining costs.

	Basic Cost	50% Reduction in material cost alone	50% Increase in material cost plus 10% Reduction in labour cost for machining
	%		
Raw material	5.5	2.75	8.25
Bought out items	4.5	4.5	4.5
Labour - M/C	70.0	70.0	63.0
- Assembly/Test	20.0	20.0	20.0
	100.0	97.25	95.75
SAVING	=	2.75%	4.25%

TABLE 2 : SAVING THROUGH IMPROVED MATERIAL

The contribution which changes to processing can make must also be considered. A simpler process which, because of the method of cost estimating may not show a direct influence on manufacturing costs, may well result in reduced overheads by requiring a lower input of energy or processing materials or by giving rise to less scrap or need to rework. A process which requires less time for associated operations will directly influence manufacturing costs. For example, heat treatment in a vacuum will remove the need to perform any post heat treatment cleaning operation and also, in many instances, the need to grind after hardening. In the latter case there is the double benefit of the removal of the time required for grinding and the reduction in scrap arising from faulty grinding.

VALUE ENGINEERING

The principles and methods of value engineering are now well established and widely used so will not be repeated here but the Company's philosophy and attitude to the particular circumstances of its product will be discussed.

Various definitions of value engineering and value analysis will be found in the technical literature, some suggesting little or no distinction between the two. However, while using the term value engineering to cover all aspects in a general manner, it is logical for our purpose to recognise two distinct but closely related activities :

VALUE ENGINEERING is an organised effort to provide the necessary functions in a new product at the lowest total cost measured over the life cycle of the product.

VALUE ANALYSIS is an analytical technique designed to examine all the elements of cost and function of an existing product in order to determine whether or not any item of cost can be reduced or eliminated whilst retaining all functional and quality require--ments.

As defined here the first of these two techniques, value engineering, is by far the most important in the aircraft industry because of the very high cost of re-approval and administration when design changes are introduced into an existing, proven product. Value analysis, however, can be applied as a continuing procedure throughout the production life of a product and will benefit both from the manufacturing and operating experience gained. It can be particularly rewarding in revealing excess costs generated by high scrap rates or from rework necessary to correct non-conforming parts.

The role of value engineering in the product cycle is shown in Fig 4. In order to make its greatest impact on costs it must be given serious consideration as early as possible, certainly at the definition stage. However, because many of the members of a value engineering team do not have the designers facility to visualise a complex technical concept in terms of actual hardware, true value engineering really begins at the design scheme when the first drawings of the proposed system become available and a preliminary selection of materials has been made. It is therefore imperative that the designer responsible for these drawings should have a good knowledge of the principles of value engineering otherwise the value engineering team may find itself offering a fundamental--ly poor design for the lowest cost. The simple rules taken from a Company standard on value engineering and given here in Appendix 1 draw the designer's attention to these principles.

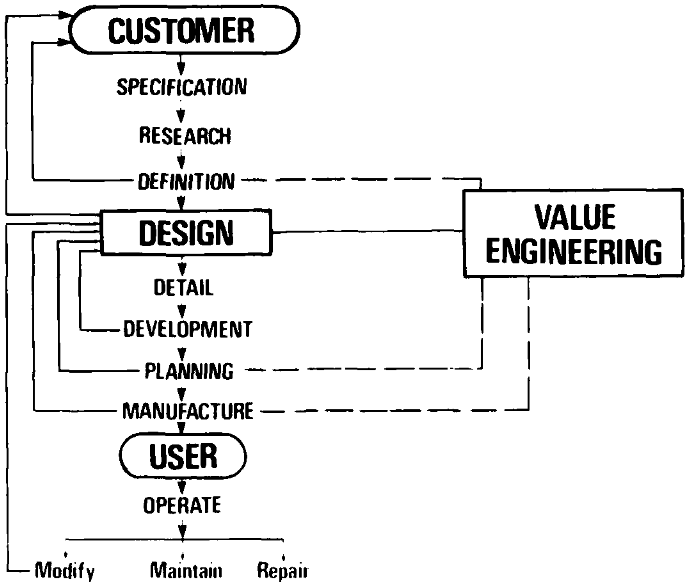

FIG 4 - THE ROLE OF VALUE ENGINEERING IN THE PRODUCT CYCLE

Feed-back to design occurs at many stages in the cycle as a result of development, manufacturing problems and ultimately through the need to incorporate modifications arising from service experience. Each time this occurs the affected parts should be re-assessed to optimise costs.

MANUFACTURING LEAD TIME

Although not a primary consideration of value engineering, manufacturing lead time is a most important factor. In the typical short batch production of aircraft accessories a large proportion of the lead time required for manufacturing consists of queueing time between different machine tools or processes, rather than the actual time taken to perform the operations themselves. A part requiring many operations to be performed on one machine tool may well have a shorter lead time than another which requires a smaller total number of operations to be carried out on several different machines.

Thus, if by judicious design the number of different types of machining or other processes can be reduced the lead time will also be reduced because of the smaller number of work movements. This will not always appear as a visible effect on costs but can be taken as an additional bonus. For instance, hardening a case-hardened part all over instead of selectively hardening, via copper plating, will save the time for two trips to the plating shop (plating and de-plating) and for machining copper from those areas required to be hard or alternatively masking them before plating.

THE VALUE ENGINEERING TEAM

Formal value engineering is carried out by a small team of experts co-ordinated by a specialist value engineer. The members are drawn from the specialist departments which the diligent project designer will in fact have consulted during his initial design process. The team approach merely recognises the benefit of gathering these people together, so that, by the free interchange of ideas and viewpoints the most cost effective design can emerge. Because of the labour intensive character of fuel controls this implies the smallest number of component parts produced by the least amount of labour.

The constitution of our basic value engineering team is shown in Fig 5. Two points are considered to be of particular importance.

Firstly, the participants must be widely experienced and of a sufficiently high level of seniority to ensure that decisions made within their particular functions will be upheld.

Secondly, with the exception of the value engineer, the team members are dedicated to the project under review. The use of a project dedicated team ensures the swiftest implementation of value engineering recommendations and avoids the rivalry which can often develop with a team operating from within a separate value engineering department.

VALUE ENGINEER Chairman Secretary

PROJECT DESIGNER

PROJECT DEVELOPMENT ENGINEER

SENIOR PRODUCTION ENGINEER

SENIOR COST ESTIMATOR

IMPORTANT
- **Level of Seniority**
- **Dedication to the Product Under Review**
- **Other Specialists Co opted as Required**

FIG 5 - THE BASIC VALUE ENGINEERING TEAM

It is also possible to set up a team under a suitably trained chairman who is only temporarily seconded to the value engineering function for the duration of a particular exercise. While it is not essential for such a person to be a practising engineer he clearly must be well orientated towards engineering as is, for instance, a metallurgist. The co-option of people to act as team leaders from a wide variety of functions has the benefit of spreading the concept and acceptance of value engineering more widely throughout the organisation.

In terms of the optimum use of available manpower so as to achieve the maximum results in the shortest time it is our experience that a small dedicated team offers significant advantages over a larger, wider ranging team. From time to time however, but only to solve specific problems, the basic team is re-inforced by the co-option of relevant specialists from other functions such as Buying, Quality, Service Engineering, Materials Engineering,etc.

PLANNING

The time available for a value engineering exercise on a new product is frequently very restricted because of the demands imposed in rapidly arriving at a potentially successful design to meet the technical specification which can be offered to the engine maker at a competitive price. For this reason the exercise may be completed in two stages, firstly before the sales bid is made in order to remove any serious cost anomalies and secondly when the successful design scheme is detailed for production.

Careful planning of the exercise is therefore very important and follows this general pattern for a complete system.

1 Presentation of targets set by the management for :

Manufacturing Cost

Market Potential - units per year

- total units

Completion date for value engineering

2 Brief introduction by the project designer on the purpose and mode of operation of the equipment.

3 Brief general impressions of the team on the design as it stands, highlighting potential problem areas.

4 Divide the control into functions -

e g. Pump, spill valve, metering valve, etc, etc.
Sub-divide each of these major items into appropriate sub-functions.

5 Indicate which functions/sub-functions/components might have wider application to other engines or systems.

6 Indicate which components are likely to require major development.

7 Establish order of priority for detailed value engineering analysis.

8 Analyse the equipment function by function -

a) Appraisal of method of achieving the function

b) Appraisal of each component

9 Across the board reviews at appropriate times with specialists on relevant topics, such as sealing, bearings, standardisation, servicing and maintenance, etc.

PRESENTATION OF COST DATA

It is vitally important for the team to be fully aware of the factors contributing to costs, of their magnitude and their relative importance. It is only in this way that best use can be made of the available time by attacking the principal cost drivers. Graphical presentations derived from primary cost data supplied by the Cost Estimating Department have been found to be of great value in providing a focus for the endeavours of the team. Examples of typical graphical presentations which have been used in a recent value analysis exercise on a solenoid valve which has identified potential savings of the order of 9.5% are shown in Figures 6 to 8.

Fig 6 shows the basic cost structure for the solenoid valve. This is similar to the typical example already given (Fig 3) in that labour for machining operations is the main cost driver. At 9% the cost of bought-out items is somewhat higher because of a requirement in the customer's specification to fit a particular electrical connector which alone accounts for 7% of the total cost of the unit.

The solenoid valve has four primary assemblies, the functions of which are :

PRIMARY ASSEMBLY	FUNCTION
Valve	Permits/stops fuel flow
Solenoid	Operates the valve
Electrical connection	Activates the solenoid
Heat Shield	Protects the assembly

The value of the individual assemblies in relation to their cost can be assessed by reference to the presentation which is shown in Fig 7 which also serves to highlight unacceptably costly sub-assemblies such as the orifice assembly, the anvil and the coil tube assembly.

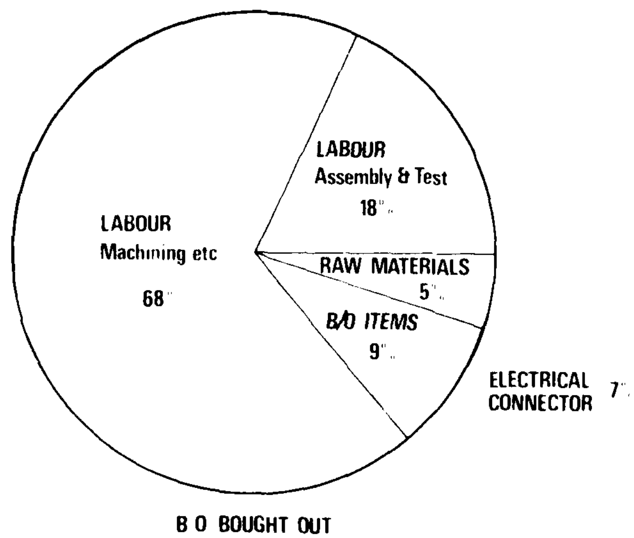

FIG 6 - COST STRUCTURE OF A TYPICAL SOLENOID VALVE

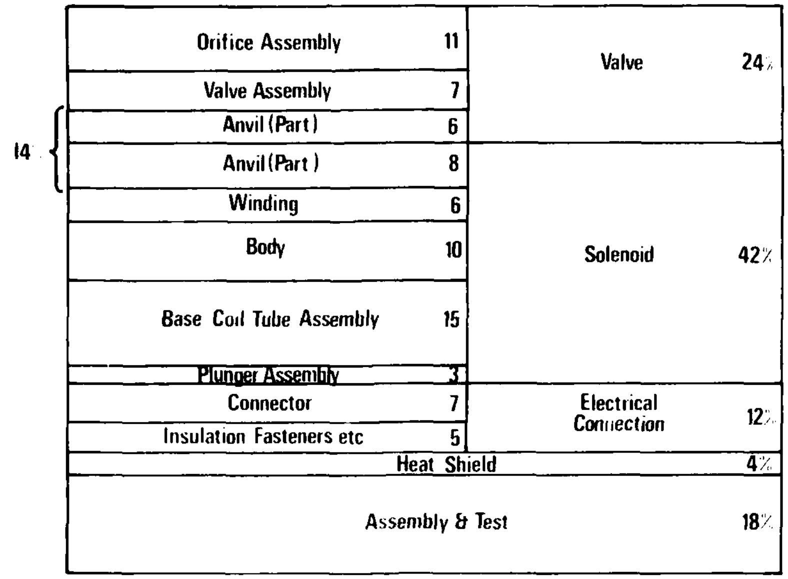

FIG 7 - DISPOSITION OF COSTS IN A TYPICAL SOLENOID VALVE

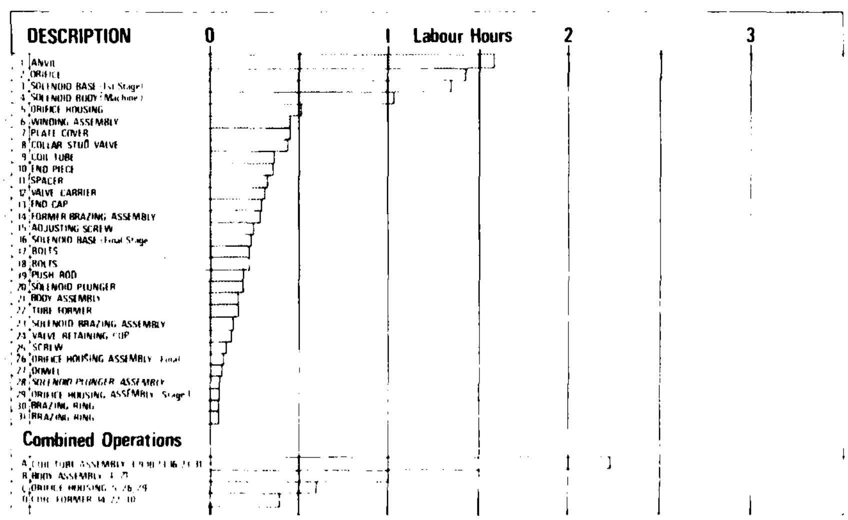

FIG 8 - SOLENOID VALVE - ANALYSIS OF LABOUR

Having established that labour for manufacturing is the most important cost driver it is necessary to carry out an item by item analysis, concentrating effort on those of highest labour content. The bar chart shown in Fig 8 clearly indicates that most of the labour is expended on a small number of the items. In this example 25% of the components account for 65% of the labour. Particular attention must also be paid to those items (marked by asterisk) which are common to other assemblies. These are capable of yielding additional benefits provided that the suggested changes are acceptable in all cases. If the modifications cannot be universally adopted careful consideration must be given to the possible penalties resulting from more than one standard having to be used.

RELATIONSHIP OF FIRST COST AND LIFE CYCLE COST

In any value engineering exercise attention must be paid both to first cost and to the probable life cycle cost. First cost can be calculated with reasonable accuracy but life cycle cost is much more difficult to estimate.

In many cases features which are introduced into a design to improve reliability or to give longer life are reflected in an inherently higher first cost which to be justified must be outweighed by the benefits offered. For instance, in the development of their piston type fuel pumps to withstand fuels of low lubricity and doubtful quality, Lucas Aerospace can now offer fuel pumps which will last for many thousands of hours under these adverse conditions which might induce failure in a standard pump in a relatively short time. Because of the extensive use of metallised carbon, tungsten carbide and advanced polymers in their bearings the construction of the long life pumps is much more complex thereby demanding a high cost premium as compared to the standard pump. Whether this additional cost is worthwhile in a particular instance must be judged on the service conditions which are likely to be met.

In the course of value engineering features may be revealed which are considered to present reliability or lifing problems within the requirements of the technical specification. Alternative solutions will be offered for these features even if they lead to some increase in first cost.

Fortunately, not all items which reduce life cycle costs adversely affect first cost. For instance, the wider application of standard parts in a design will not only lower first cost but will also give reduced overall costs together with improved spares availability. In the case of locking washers which are used to secure ring nuts we have introduced a design which is not only lower in first cost but also reduces overhaul and repair costs by avoiding an expensive throw-away item. The two designs are shown in Fig 9. The improved version is a two piece construction which separates the thin cup which is deformed into the ring nut slots from the thicker base and anti-rotation dog. The original one piece design in soft austenitic stainless steel had of necessity to be machined from solid to provide adequate strength in the dog, whereas in the improved design both pieces are simple pressings. Only one of these, the cup, is replaced on overhaul.

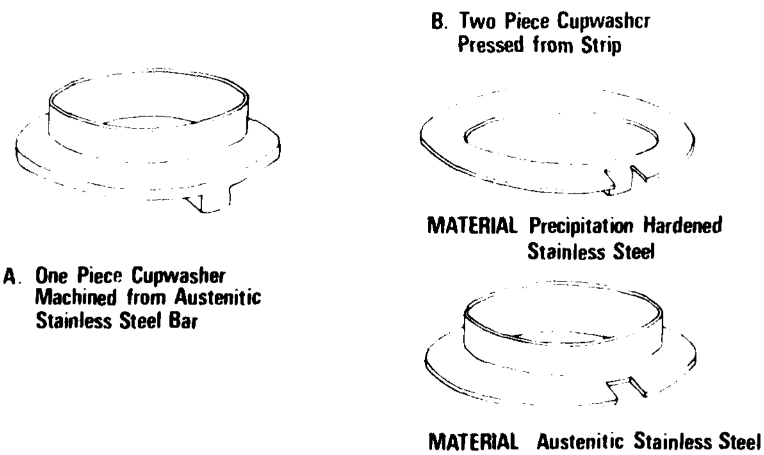

FIG 9 - FABRICATION OF LOCKING WASHER

RESULTS ACHIEVED

The savings which can be realised by the value engineering of a new product or value analysis of an existing product clearly depend upon the cost efficiency of the original design.

It is our experience that potential unit savings of the order of 20% can be expected from value engineering at the design scheme stage. Even greater benefits can sometimes be achieved by radical changes at the definition stage. These rewards are large and cost little more than the time and effort expended by the value engineering team and other co-opted specialists.

For example, in a recently completed exercise on an advanced control an estimated potential unit saving of £2680 or 19% was gained for a total expenditure of 1286 man hours. The progress of this project is shown in Fig 10. In this particular instance approximately 50% of the components unique to the control were amended or deleted to produce the savings.

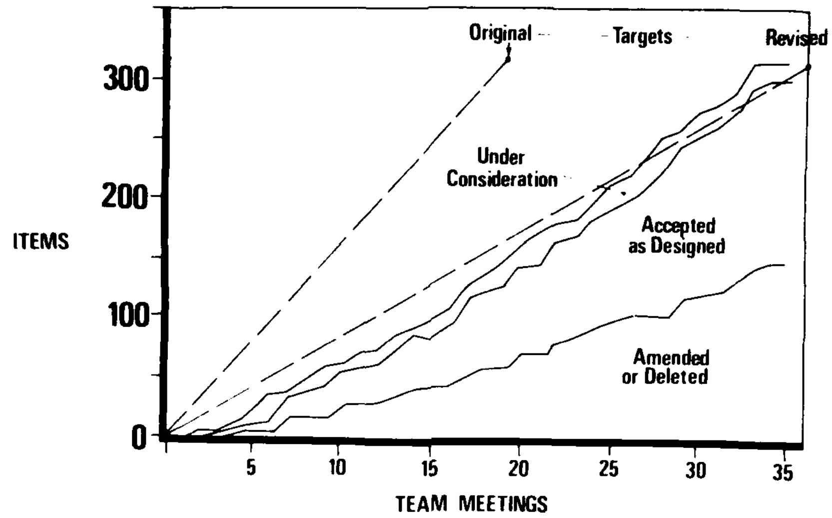

FIG 10 - VALUE ENGINEERING OF A TYPICAL FUEL CONTROL

No changes were made to standard items and, to avoid adverse interactions, no components which were common to other equipment already in production were altered. The improve- -ment with time of the performance of the team which is a normal feature of such operations can be seen clearly in this example. Another point which should be noted is the re-establishment of a realistic completion target when, after about 16 meetings, it became evident that the initial arbitrary target would not be attainable.

Because of the need to maintain interchangeability so as to avoid service problems the rewards which can be achieved by value analysis of an existing design which is establish- -ed in production are not so great, unit savings of 8 - 10% being typical in our experience. Also, to arrive at a final assessment of the real value of an apparently attractive modification it is important to take into account the cost of implementing the change. All contributory factors must be quantified including engineering costs associated with re-proving the parts, tooling costs and administration costs, not forgetting the important area of service engineering. It must also be remembered that costs might be incurred not only by the supplier but also by the customer and the operator.

CONCLUSIONS

Value Engineering using small project dedicated teams has been applied profitably to the design of hydromechanical controls for aircraft engines.

Greater savings can be realised at the initial design scheme stage than are possible by value analysis after it has entered production.

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APPENDIX 1

RULES FOR COST EFFECTIVE DESIGN

MINIMISE

Number of components
Number of machining operations
Number of untried design solutions
Number of non-standard items

AVOID

Difficult materials
Difficult machining operations
Difficult processes
Costly throw-away items

RELAX

Tolerances
Fits
Surface finishes

SIMPLIFY

Assembly
Testing

BUT

Do not forget that these "rules" are generalisations and their effects will interact. Therefore an overall view must be maintained at all times so as to ensure that each necessary function is provided at lowest cost.

NOTES

Most of the "rules" given above are fairly self-explanatory but for clarity some are enlarged upon below :

FACTORS AFFECTED BY THE NUMBER OF COMPONENTS IN THE PRODUCT

Design
Detailing
Machining content
Shop floor handling
Tooling
Assembly
Inventory

BUT : It may be preferable to separate a part of a complex component which will be subject to deterioration in service and so avoid a costly throw-away item.

POTENTIAL PROBLEMS ARISING FROM UNTRIED DESIGN SOLUTIONS

Might not work
Need for proving
Need for development
Need for modification
Need to convince the customer

BUT : Too rigid adherence to the principle should not be allowed to stifle good creative design.

BENEFITS OF USING STANDARD ITEMS

(a) Standard parts :

Reduced design and detailing costs
Greater technical background
No development costs
No proving costs
Lower inventory costs
Shorter lead time
If a national standard - no in-house manufacturing costs
If a company standard - reduced tooling costs
- economy of quantity

(b) Standard materials :

Greater technical background
No development costs
Ease of supply
Shorter lead time

FACTORS AFFECTING DIFFICULTY OF MATERIALS

Availability - only one supplier
- overseas sourcing
Problems at suppliers - Castability
- Formability
- Quality
Manufacturing properties e g : Machining
Forming
Joining
Plating
Heat Treatment
Engineering properties
Quality
Reliability
Cost

DIFFICULTY OF MACHINING OPERATIONS

Unnecessarily complicated machining operations should be avoided. The following are particularly undesirable :

Holes drilled at an angle to the surface
Deep holes intersecting at acute angles which give rise to deburring problems
Internal undercuts
Flat bottomed holes where a drill point would suffice
External protrusions on otherwise circular machined surfaces, e g.anti-rotation dogs on flanges.

The following typical machining processes are listed in order of increasing difficulty.

Least difficult :	1	Grinding
	2	Sawing
	3	Single point turning
	4	Planing and shaping
	5	Shallow drilling
	6	Milling
	7	High speed, light feed screw machining
	8	Screw machining with form tools
	9	Boring
	10	Deep drilling
	11	Generation of gear teeth
	12	Tapping
	13	External broaching
Most difficult :	14	Internal broaching

FACTORS AFFECTING DIFFICULTY OF PROCESSES

Availability - can it be done in-house ?
- if outside, is there more than one supplier ?
Ease of application
Operator skill
Environmental/Health/Safety
Quality
Reliability
Cost

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Cost control

14. Abstract

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